A Housing Energy Management Program Report

Energy
Ontario

THERMAL AND ENVIRONMENTAL PERFORMANCE OF THE AYLMER SENIOR CITIZENS' RESIDENCE

FINAL REPORT

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EXECUTIVE SUMMARY

This study examined the thermal and environmental performance of the Aylmer Senior Citizens' Residence. The building was designed to be energy efficient; besides a well insulated envelope, it included a solar space and domestic hot water heating system with annual heat storage and heat recovery on exhaust air.

Although there were some early problems with the solar heating system, storage tank and the data acquisition system, these systems operated fairly reliably after November 1981.

Four years of monitored data on the building was examined and the period December 1981 to November 1982 was selected as being the most representative of building performance.

The building has a combined annual space and water heating load of 473 GJ; 47% of this or 222 GJ is met by solar.

Building space heating load of 278 GJ was 22% higher than design. This was mainly caused by higher heat loss coefficient and interior temperature. The actual building heat loss coefficient of 330 W/°C was 15% higher than the design value probably due to open windows during the heating season. Domestic hot water consumption was almost three times higher than the design consumption of 68 GJ. Seventy-two percent of the energy supplied to the domestic hot water system is used to meet the water load; the other 28% is required to overcome tank and piping losses. It appears that the water heating load was underestimated at the design stage. These higher heating loads are the main reason the solar heating system is supplying a smaller percentage of the total heating load than anticipated by the system designers (47% actual as opposed to 92% design).

The solar system annually collects 291 GJ or 1.58 GJ per square metre of collector aperture area, 24% below the design estimate of 384 GJ. A smaller collector area and poorer collector performance characteristics than used in the design estimate account for one third of the difference. Most of the rest of the difference is due to inefficient heat delivery. The reflector increased solar radiation on the collector by approximately 8%.

The solar heating system was found to annually deliver 222 GJ or 1.2 GJ per square metre of collector, 18% less heat than expected. Two factors in the system operation account for the lower performance. First, for most of the winter, solar heat and the electric boiler are used each day in order to use solar heat more uniformly throughout the winter. If solar heat is used continuously, the tank temperature would drop more rapidly and full electric heat would be needed for space heating in the last half of winter. During that period, however, the tank would still be at a high enough temperature to supply heat to the domestic hot water load. Second, the solar heating system has been unable to supply the domestic hot water load during the summer. These two factors result in the solar storage tank being at a higher temperature than necessary. The high storage tank temperature and thus high collector inlet temperature result in lower collector efficiency (because of higher collector heat loss).

If solar heat is used continuously until the storage tank becomes too cold for space heating and the system is modified to allow for year round solar heating of domestic hot water, solar heat delivery could become 264 GJ annually, 97% of the design energy supply (although still only 56% of total load).

Heat losses from the main solar storage tank were only 61% of the design estimate. The main reasons for the lower heat loss are lower tank water temperatures and a 17% lower tank heat loss coefficient. During the summer months (i.e. heat collection) the storage had a temperature difference from top to bottom of four Celsius degrees. When heat is drawn from the tank there is almost no temperature stratification.

The heat wheel heat recovery system was found to be operating efficiently (62%). The system, however, was found not to be supplying the design ventilation air flow rate, probably because of dirt build up in the heat wheel.

1. INTRODUCTION

1.1 Introduction to the Study

The purpose of this study is to evaluate the thermal and system performance of the Aylmer Senior Citizens' Residence. The study uses four years of detailed monitored data to determine the performance of six building systems: building shell, solar collection system, solar storage tank, heating system, domestic hot water system and ventilation system. System effectiveness is determined through a comparison of system performance as predicted during design and system performance as measured by the monitored system. The results of the study are based only on monitored data; no subsequent on-site measurements have been made.

It should be noted that, because of operational problems with the building systems and the data acquisition system, full sets of representative and reliable data are not available. Computer simulation has been used to extrapolate for missing results to provide an estimate of annual performance. It should be emphasized that extrapolation slightly reduces the accuracy of some parts of the study, since it implicitly assumes that no system failures have occurred.

Section 1 describes the building and the six building systems. Section 2 presents the data analysis technique and a description of the weather data for the analysis period. The performance of the six building systems is analysed in Section 3 along with computer simulations of potential performance as a result of improvements. Section 4 summarizes the results of Section 3 as they relate to the performance of the total building.

1.2 The Building

The Aylmer Senior Citizens' Residence is located at 58 Myrtle Street, Aylmer, Ontario (approximately 40 km southeast of London and 15 km from the north shore of Lake Erie). The residence is a rectangular, two-storey brick veneer building with 29 apartment units (see Figure 1.1). The building has an above-grade total floor area of 1784 square metres

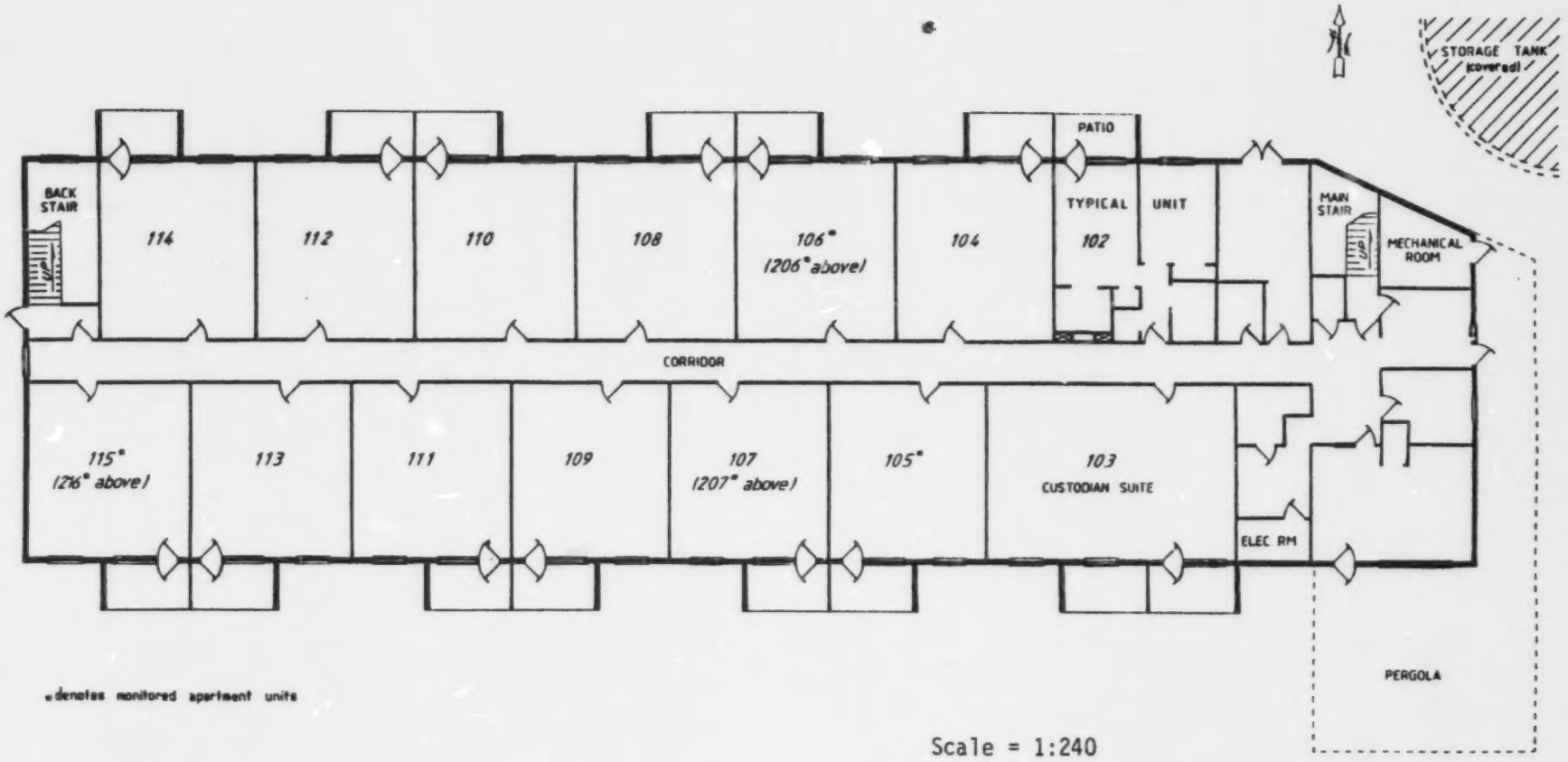

Figure 1.1 Floor Plan of Aylmer Senior Citizens' Residence

and does not have a basement. Construction was completed in June 1978 and the monitoring system was commissioned in July 1979.

The Aylmer Senior Citizens' Residence was designed to be energy efficient. Principal energy conservation features include high insulation levels, double- and triple-glazed windows, solar space and domestic water heating systems, and a heat recovery system on exhaust ventilation air. A schematic of the original building mechanical systems is shown in Figure 1.2. Figure 1.3 shows the present mechanical system schematic.

The main features of the building and building mechanical systems are discussed in the following sections.

1.2.1 The Building Shell

The building walls and ceiling have a thermal resistance of 4.84 and 7.04 $m^2 °C/W$ respectively. The walls are composed of 38 X 140 mm wood studs on 600 mm centres, filled with fibreglass insulation and covered on the exterior with 38 mm of styrofoam sheeting and face brick. The ceiling is insulated with blown fibreglass to a depth of 500 mm.

The perimeter of the slab is insulated with 38 mm of styrofoam extended 1.2 m below ground. The floor of the building is uninsulated.

The Aylmer Senior Citizens' Residence has a gross window area of 107 square metres or 6% of the floor area. Fifty-two percent of the windows are south-facing, although many of these windows are shaded by balconies for most of the year.

The building was designed to have a heat loss coefficient of 1200 W/°C and a design heat loss of 46 kW when the ventilation system is operating, and 1050 W/°C and 41 kW when it is not operating. No major modifications have been made to the building shell since construction.

On-site observations in February and May 1984 revealed several reasons why building energy consumption may be higher than designed. Many

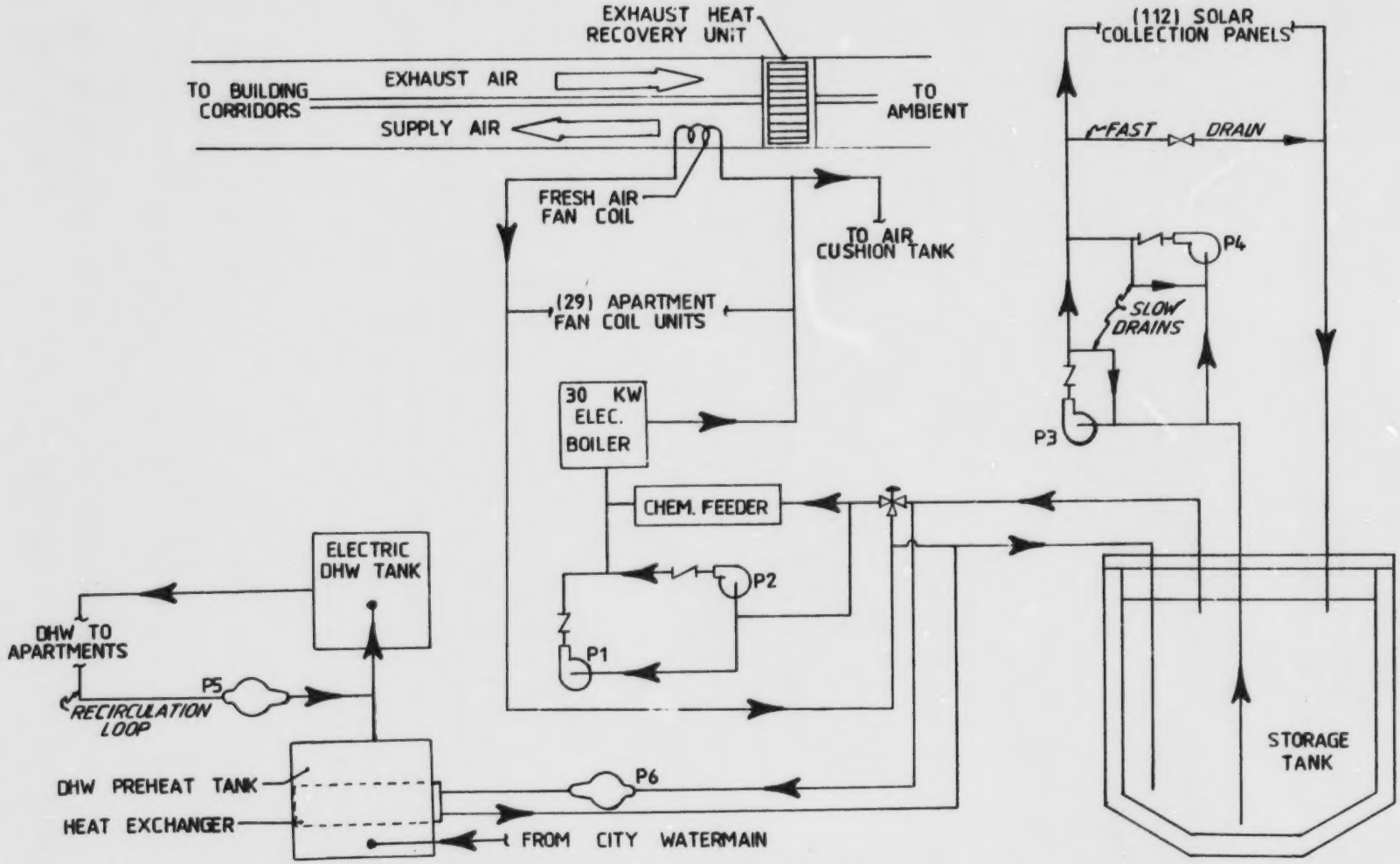

Figure 1.2 Aylmer Senior Citizens' Residence Mechanical Systems Schematic - as built

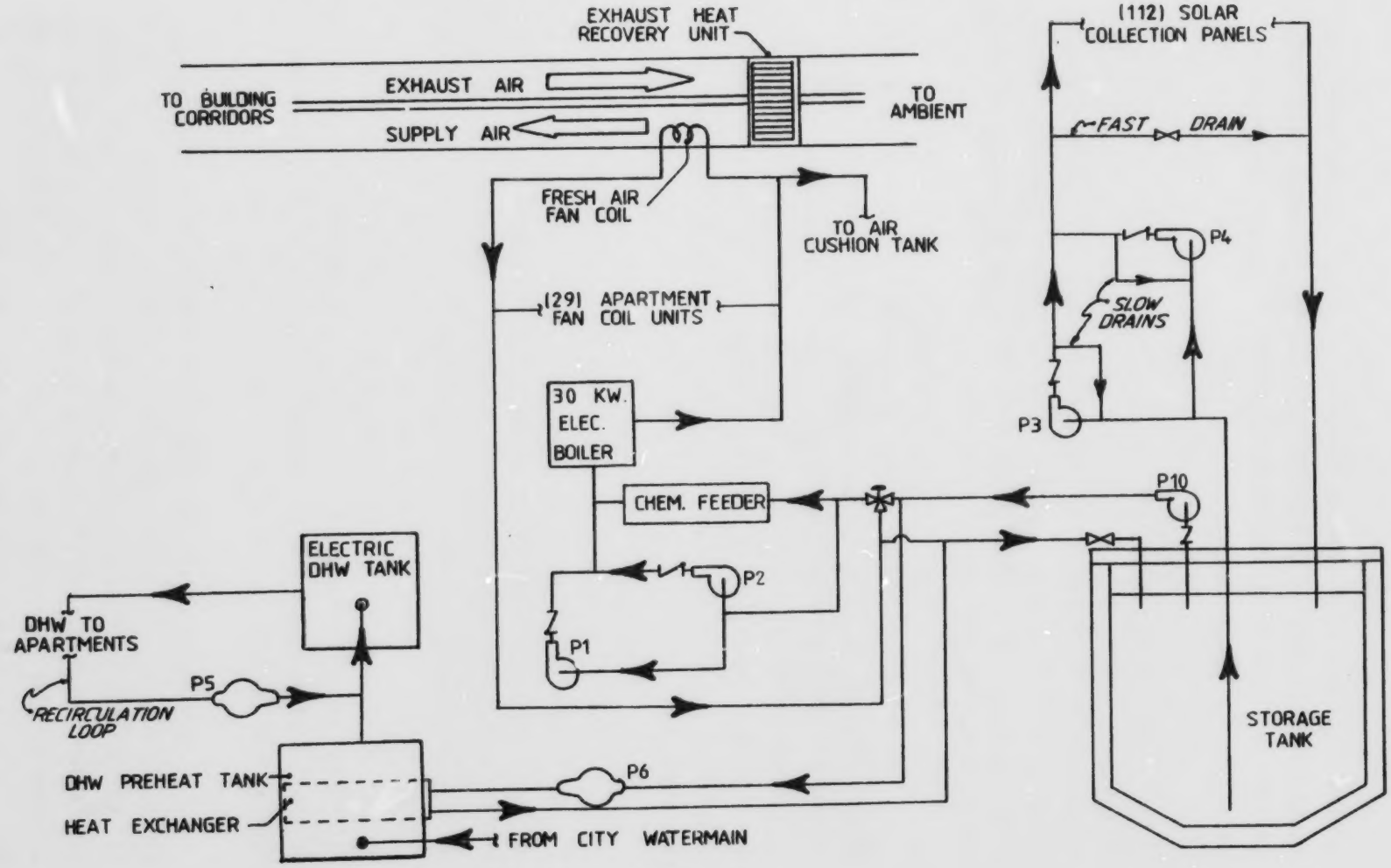

Figure 1.3 Aylmer Senior Citizens' Residence Mechanical Systems Schematic - as modified

of the units had storm windows permanently open. This permitted the double-glazed units to be open as required for increased ventilation. Several of the units on the south-side had window air conditioners installed for summer cooling.

1.2.2 Solar Collection System

The solar collection system schematic is shown in Figure 1.4. The system is a drainback system; that is, storage tank water is circulated directly through the collectors. When the pumps are shut off, the water drains back into the storage tank.

The solar collection system consists of 112 Temspec flat-plate solar collectors [1], two pumps and connecting piping. The design report [10] called for collectors of 1.95 square metres of aperture area. The collectors installed at the site, however, have a total aperture area of 184 square metres or 1.644 square metres per collector; 16% below the design area. It is not known why a smaller collector was supplied to the site.

The solar collectors are mounted on the roof in two rows of 56 panels at a 60° slope to the horizontal facing due south. The collectors are connected two-in-series in a reverse-return manner (see Figure 1.4). The system uses header pipes external to the collectors with no balancing or shut-off valves to individual collectors.

The pumps were designed to circulate water at a rate of 5.7 litres per second, from the bottom of the storage tank through the collectors to the top of the tank. After the collectors are filled, only one pump runs at a time, alternating on each start.

The solar collection system has remained largely unchanged since its design. In January 1982 four collectors started leaking and had to be isolated from the system. It is believed that this leakage was caused by water freezing in those collector pipes with insufficient or reversed slope for water drainage [6]. The four damaged collectors were isolated in April 1982 and replaced in July 1982.

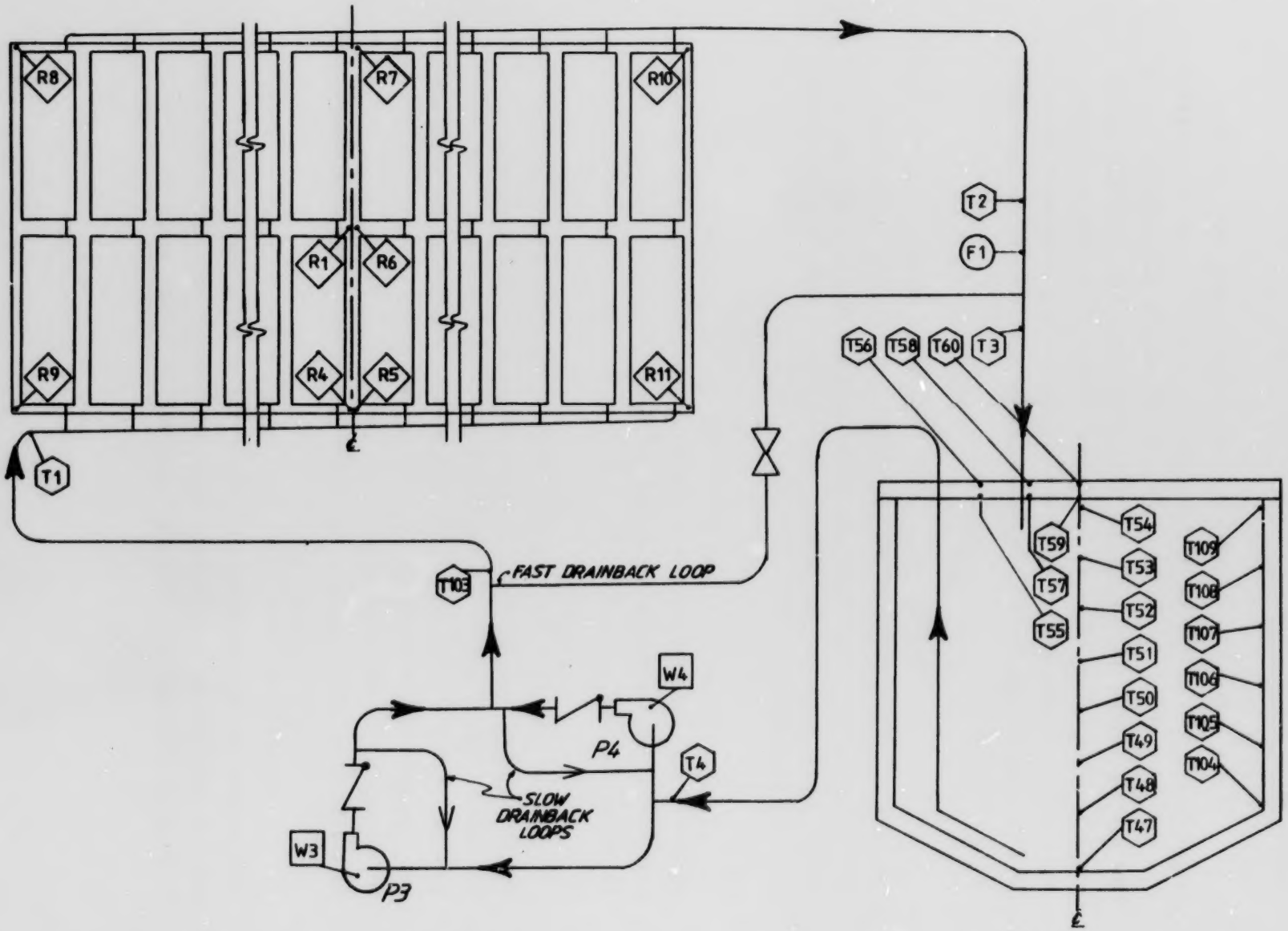

Figure 1.4 Solar Collection System Schematic

1.2.3 Solar Storage Tank

The design of the solar heating system is such that the tank stores solar heat collected in the summer for use in winter space heating. The objective of system design was to meet almost the full heating load of the building (92%). The large quantity of heat involved necessitates the use of a large volume of water for thermal storage. The tank at Aylmer has a volume of 886,000 litres or 4800 litres per square metre of collector. Tank volumes for short-term solar storage are usually 50 litres per square metre of collector.

The solar storage tank is located a short distance from the building. The tank is cylindrical with the bottom section partially tapered (see Figure 1.4). The bottom and sides of the tank are burried; the top is at the ground surface. The tank is 15 metres in diameter and 6.7 metres deep (at the centre).

The tank was designed to be insulated with 152 mm of field-applied urethane foam and covered with a waterproof lining. The concrete roof of the tank is supported by open web steel joists and insulated with 152 mm of urethane.

In July 1979 shortly after completion, it was determined that the storage tank was leaking [6]. The rate of water leakage gradually increased and by October 1979 had become 6800 litres per day. The tank was drained in February 1980. Inspections showed that the urethane insulation varied in thickness from 125 mm to 305 mm, and that cracks in the waterproofing and insulation of the tank bottom had developed. A full discussion of the reasons for water leakage are given in reference [6].

Remedial measures to the tank included the installation of new foam on the tank bottom to a thickness of 152 mm and a new waterproof coating as discussed in reference [6]. The tank was refilled in April 1981. No problems with the tank have been observed since that time.

1.2.4 Heating System

The original building space heating system is illustrated in Figure 1.2. It was intended that the solar heating system would supply almost all (96%) of the building space heating for an average year. A 30 kW electric boiler was installed to provide auxiliary heating if the temperature of the solar storage tank water was not sufficient to heat the building.

The heating system was designed to operate in three modes as described in the following paragraphs:

Mode 1 - Solar Storage Tank above 43°C

In this mode of operation, a low capacity pump (P1) circulates water at 3.5 litres/second from the bottom of the tank through the 44 fan coil units, returning the water to the bottom of the tank. A three-way valve mixes building return water to maintain building supply water at 43°C. Individual fan-coil thermostats determine whether fans would circulate building air across the coil. The fans have three-speed switches, although the lowest setting should be sufficient to meet the heating load.

Mode 2 - Solar Storage Tank below 43°C

In this mode, the high capacity pump circulates storage tank water through fan coil units at 7.9 litres/second. The three-way valve mixes building return water to maintain building supply water at 29°C. The fan operates as in Mode 1, although usually at higher speeds. The original system design included a timer-relay system to change from solar to electric heating. If off-peak power is available, the electric boiler could be used at night to extend the length of the solar heating season.

Mode 3 - Solar Storage Tank unable to heat building

In this mode, water is not drawn from the storage tank. The high capacity pump circulates water through the boiler and the three-way valve returns all water to the pump; thus, this mode is a closed circulation system. The electric boiler maintains the water at 43°C.

The heating system operated in Mode 3 (electric heat) for two winters (1979-80 and 1980-81) because of problems with the storage tank (see Section 1.2.3).

In early 1981, investigations by Dillon [6] showed that the heating system had two deficiencies. One, the heating system could not automatically switch from solar to electric boiler heating, because the system operated as a closed system when using the electric boiler and as an open system when using tank water. Manual manipulation of a number of valves was necessary to change from one heating source to another.

Two, the three-way valve was not properly controlling the water temperature to the heating system. As a result of these deficiencies a number of changes were made to the heating system; these changes were completed in August 1981 (see Figure 1.5).

The principle change to the heating system was the installation of a primary circulation loop with separate pump (P10). This pump, along with correction of the controls, allows the system to switch more easily between solar heat and electric boiler heat. The heating water outlet was relocated from near the bottom of the tank to near the top of the tank. In addition a faulty flow switch was removed in the spring of 1982.

1.2.5 The Domestic Hot Water System

The domestic hot water (DHW) system consists of two tanks piped in series (see Figure 1.6). When there is a demand for hot water, the water is taken from the 545 litre electric hot water tank, allowing city mains water to enter the bottom of the 900 litre solar preheat tank. The electric water heater is maintained at 49°C.

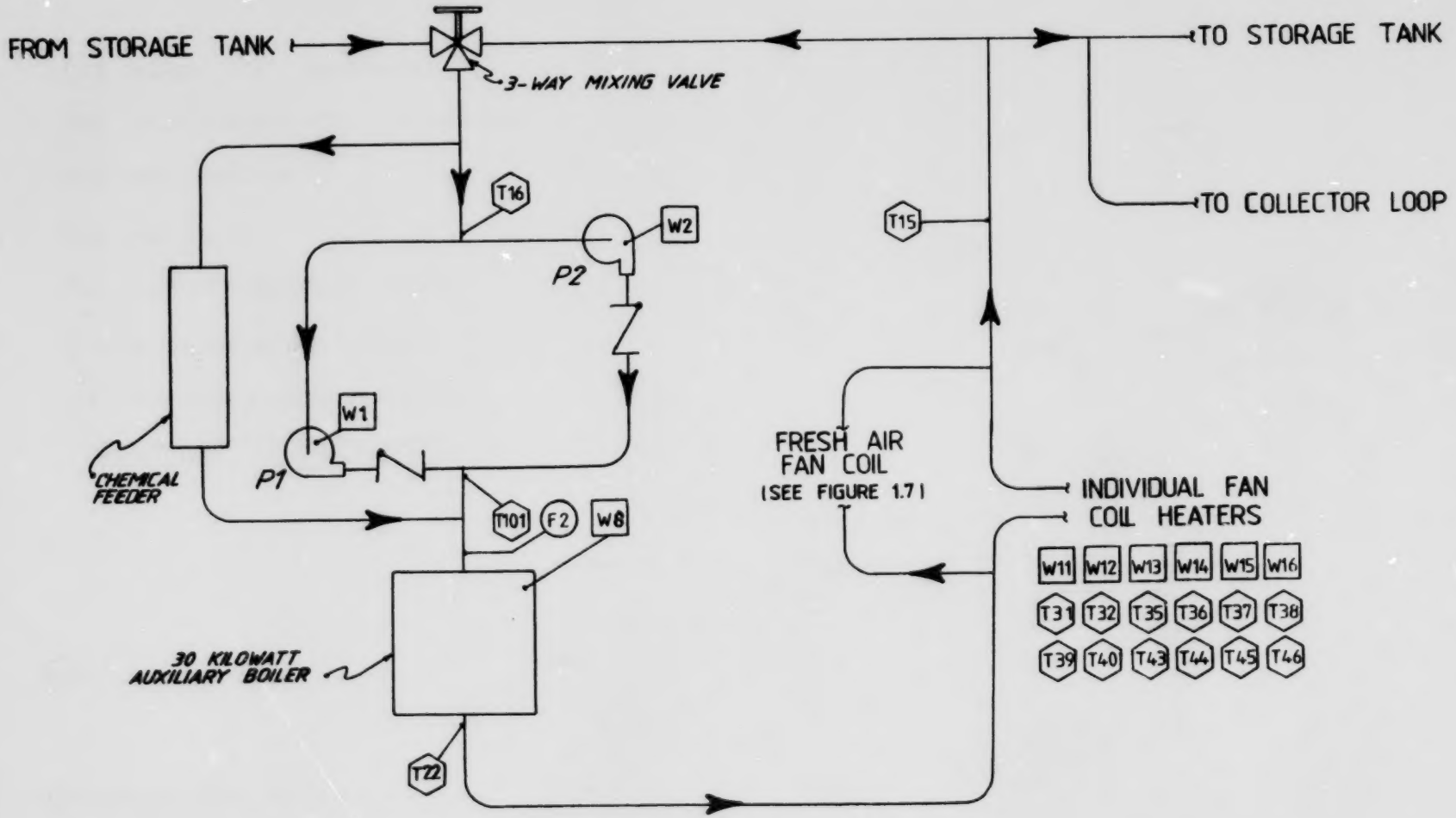

Figure 1.5 Heating System Schematic

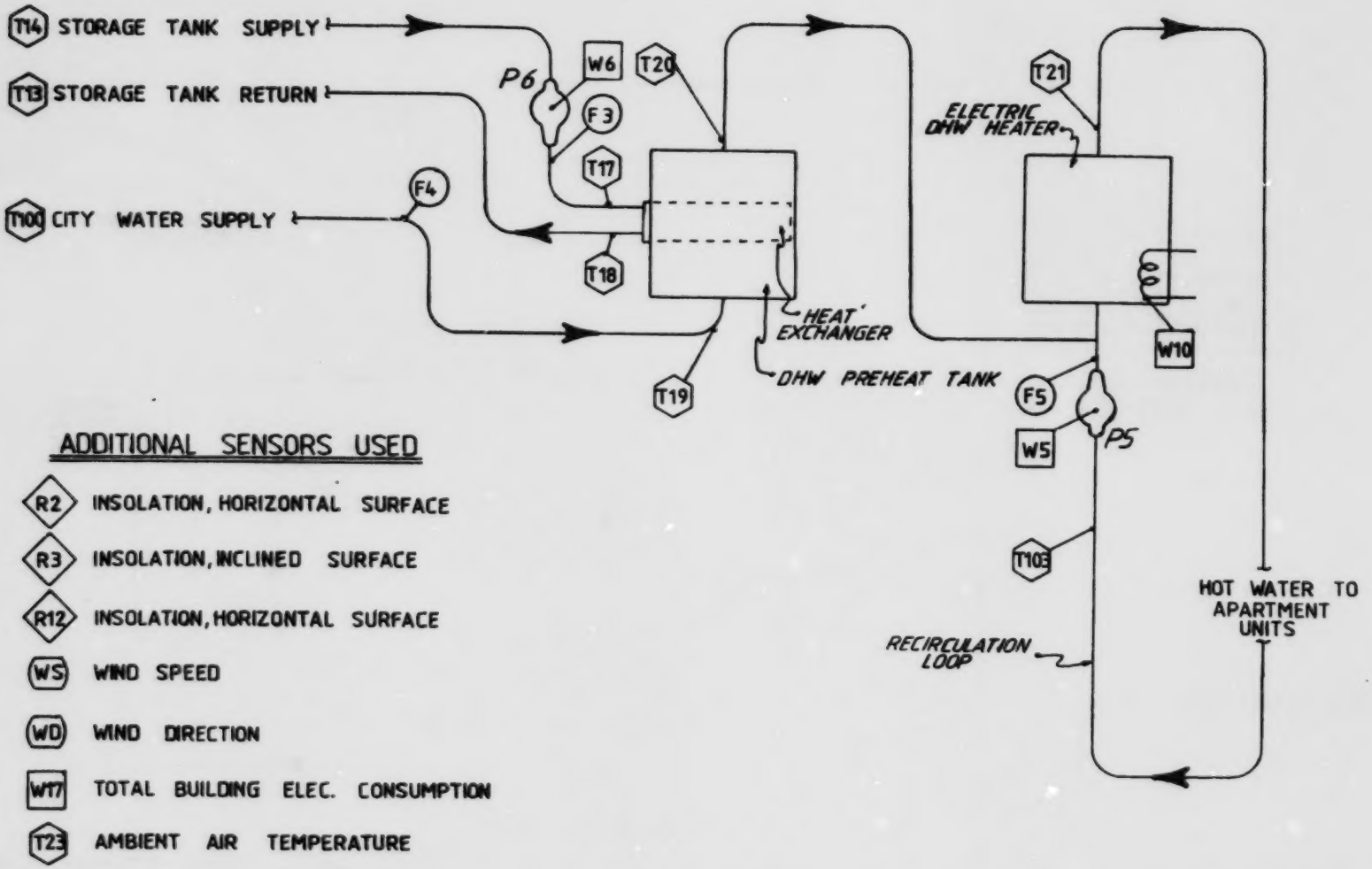

Figure 1.6 Domestic Hot Water System Schematic

Solar heat is transferred from the main solar storage tank to the preheat tank by pumping (Pump P6) storage tank water through the preheat tank tube-bundle heat exchanger. This heat transfer occurs whenever the preheat water is colder than the hot water setpoint (49°C) and the main storage tank water. If the preheat tank water entering the electric tank is not up to 49°C, a 13.5 kW electric element heats the water to 49°C. The DHW system was designed to provide 1360 litres of hot water per day.

Although it appears that the DHW system operated properly at times in 1979, Dillon [6] reported that the system was not operating properly in 1981. They concluded that Pump P6 was not able to draw water from the main storage tank. As discussed in Section 1.2.4, Pump P10 was installed in August 1981 to provide a positive pressure to the heating system. If Pumps P10 and P6 are operating, then storage tank water can be delivered to the DHW system. Pump P10, however, does not operate when the space heating system is shutdown for the summer. Thus, no solar heat is supplied to the DHW system for approximately five months of the year.

1.2.6 The Ventilation System

The ventilation system for the building uses a packaged air handling unit consisting of two 2.2 kW fans for supply and exhaust air and a heat recovery wheel (see Figure 1.7). The design called for the building to be under a slightly negative pressure, with the exhaust air rate of 1540 litres/second exceeding the supply air rate of 1380 litres/second. Fresh air is supplied to the central corridor and exhaust air is taken from the kitchens and bathrooms. The ventilation system is shut down between 10 P.M. and 7 A.M.

A hot water coil is placed in the supply air duct downstream from the heat recovery wheel. A temperature sensor modulates a control valve to the hot water coil to maintain the supply air at 21°C. Heat for this coil is supplied by the electric boiler or from the main solar storage tank as described in Section 1.2.4. A freezestat shuts down the ventilation system if the supply air temperature falls below 4.4°C. The heat wheel is not operated during the summer.

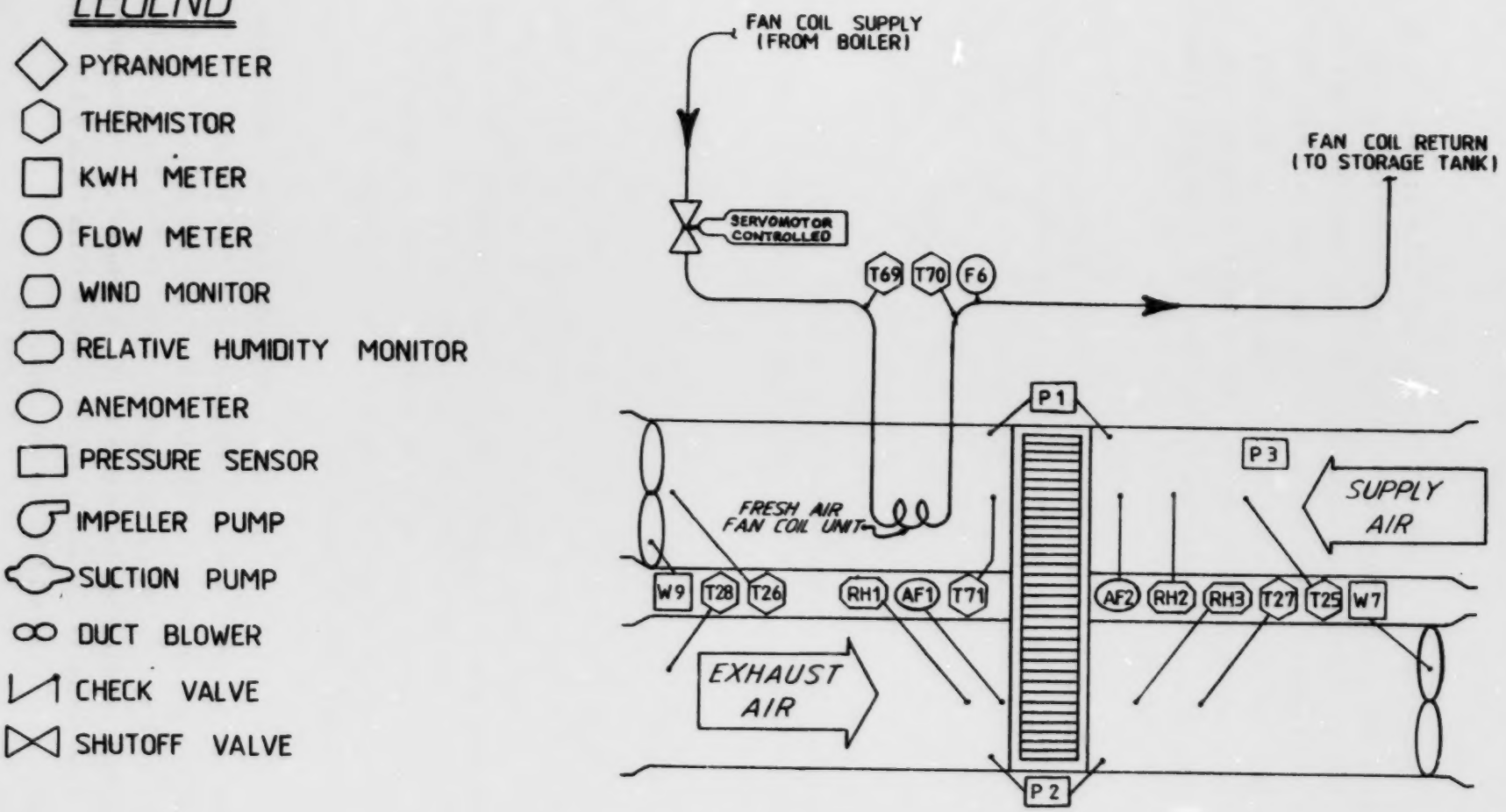

Figure 1.7 Ventilation System Schematic

1.3 The Data Acquisition System

Because of the uniqueness of the building heating systems, the National Research Council, with the assistance of Davis Engineering Limited, installed and maintained an extensive data acquisition system. One hundred and sixteen sensors were installed to measure temperatures, solar radiations, flow rates and electricity use (see Figures 1.4 - 1.7). The measurement points taken for each of the building mechanical systems are given in Tables 1 through 6 of Appendix A. These sensors were connected to a Digital Equipment Corporation LSI-II minicomputer with 28 K memory and dual floppy disk drives. Analogue sensor outputs were converted to digital output by a Monitor Labs scanner and a Fluke 8500 multimeter. Raw data from the 116 channels was typically stored on disk at five minute intervals. This data was subsequently transferred to 9 track magnetic tape. In addition to recording the raw data the minicomputer also performed daily integrations of key performance measurements. Each month the daily integrations were printed and included as a part of the monitoring contractors report. A full description of the data acquisition system is given in reference [5].

The data acquisition system was installed in early 1979 and commissioned in June 1979. The system operated 79% of the time through to May 1980. Problems encountered during this period included improper installation of some thermistors and electrical meters, failure of the floppy disk drive and several errors in the computer software doing the daily integrations.

After the solar storage tank was drained in 1980, the data acquisition system was shut down until the tank could be repaired. The system was re-started in March 1981. During the summer of 1981 there were several hardware failures including two power supplies, disk drive, data scanner and computer processor boards. It was suspected that the cause of these problems was the high ambient temperature in the monitoring equipment room. Hardware problems were corrected in November 1981, and an air conditioning unit was installed in March 1982. The data acquisition system performed fairly reliably until March 1983 when it was removed from the site. A full description of problems encountered with the data acquisition system are given in references [2, 3 and 4]. An NRC summary of solar heating system performance, based on the recorded raw data, is presented in reference [13].

1.4 Expected Thermal Performance of the Building

In their design report [10], Hooper and Angus Associates Ltd. present the expected energy use of the building. Their projections are presented in Table 1.1. The performance of the solar heating system was estimated using an early version of the ASTEP computer program [12].

Many energy-based computer programs have been developed and many others improved since the initial design calculations were prepared. In order to check the suitability of the design energy consumption figures, it was decided to perform computer simulations using the most up-to-date programs.

Three solar simulation programs could be used for the analysis: ASTEP, WATSUN and ENERPUB. ASTEP is an hour-by-hour computer model developed by the University of Toronto for simulating annual storage solar heating systems. The limitations of this program are the simple building heat loss model, no pipe heat loss effects and a fully-mixed storage tank model. WATSUN, developed by the University of Waterloo, has the same limitations as ASTEP. ENERPUB is an hour-by-hour computer program developed by Enermodal Engineering Limited for Public Works Canada and is based on WATSUN. This program contains several extensions to WATSUN including a stratified storage tank model and a pipe heat loss model. It is felt that ENERPUB is the best program to use in this case for evaluating the performance of the solar heating system.

The results of the ENERPUB simulation of the building are presented in Table 1.1 (see Appendix D for full program outputs). Several assumptions were required about the building characteristics and operation in order to perform the simulations; these are discussed below.

Table 1.1: Expected Thermal Performance of Aylmer Senior Citizens' Residence

	Design (GJ/yr)	Predicted by ENERPUB (GJ/yr)
Space Heating Load	227	227
Water Heating Load	68	68
Solar Energy Collected	384	387
Solar Energy Delivered	272	272
Storage Losses	112	115
Solar Heat to Space	217	225
Auxiliary to Space	10	2
Solar Heat to DHW	55	47
Auxiliary Heat to DHW	13	21
Percent Solar	92%	92%

Most of the inputs for the ENERPUB program were taken from the design reports [9,10]. The infiltration rate was assumed to be the difference between the exhaust and supply air flow rates. From the manufacturer's product literature, the heat wheel was calculated to have a heat exchange effectiveness of 0.78.

A major contributor to the building heating load is the internal heat gain (due to lights, appliances, people etc.). The value used in the design calculations is not known. For this building the internal heat gains were assumed to be 575 MJ/day. From the values given in the design report [9] the design daily hot water load can be calculated to be 1140 litres per day. The collector area in the design report [10] (218 square metres) was used in the ENERPUB program.

2. METHOD OF ANALYSIS

2.1 Selection of Data

The purpose of this section is to describe the procedure for selecting appropriate monitoring data for system analysis. The performance of the building systems at the Aylmer Senior Citizens' Residence was monitored for a period of almost four years. An investigation of the performance of the various building systems requires a review of the monitored data, since much of the data is not representative of typical system performance or is invalid or incomplete.

Because of the experimental nature of many of the building systems (especially the solar heating system), there were many start-up problems. It is felt that the performance of these systems during periods containing start-up problems is not indicative of the potential or long-term performance; thus, only those periods when the systems were operating as designed were considered for evaluation.

The NRC daily summaries were examined for suitability of monitored information for each of the six building systems under study: building shell, solar collection system, solar storage tank, space heating system, DHW heating system, and ventilation system. The results of this initial examination are presented in Appendix B. Table 2.1 summarizes the analysis period selected for each of the six systems.

2.2 The Analysis Period

The analysis period for the six systems examined in Appendix B cover the same period: November 21, 1981 to March 31, 1983. In this section the suitability of the weather to be representative of long-term performance is discussed. For example was this period unusually cold or sunny.

Table 2.1 Analysis Period for the Six Building Systems

	Analysis Period		
Building Shell	November 1981	to	May 1982
	September 1982	to	March 1983
Solar Collection System	March 1982	to	November 1983
Storage Tank	November 1981	to	March 1983
Space Heating System	November 1981	to	May 1982
	October 1982	to	March 1983
DHW System	November 1981	to	May 1982
Ventilating System	November 1981	to	February 1982

The two weather conditions that most affect the performance of the systems are ambient temperature and solar radiation. Wind speed and wind direction, although smaller in impact, can affect performance. There is often, however, no relationship between wind speed and direction at the weather station to that at a different site because of local obstructions.

Figure 2.1 shows daily average values of ambient temperature as measured at the Aylmer Senior Citizens' Residence (missing values are skipped). The figure shows the sinusoidal variation in ambient temperature throughout the year. It is quite clear that the winter of 81 - 82 was much colder than the winter of 82 - 83. The large fluctuations in daily values make it difficult to compare to the long-term average temperatures.

Figure 2.2 shows the number of degree-days below 18°C for the site and period of study. The dashed line shows the long-term average degree-days for the Aylmer weather station. The figure shows that degree-days totals (area under the curve) are almost identical for the one year period ending November 1982 (site value is 3749°C-days, long term value is 3841 °C-days). The winter of 1982 - 83 is, however, considerably warmer with 15% fewer degree-days (December 1, 1982 to April 1, 1983).

Figure 2.3 shows monthly values of solar radiation on a surface inclined at 60 degrees. The solid line represents the solar radiation measured at the centre of the solar collector array (including solar radiation reflected onto the array by the reflector) for the period December 1981 to November 1982. The dashed line represents an estimate of the long-term solar radiation on the inclined surface for London, Ontario. These values were determined using Atmospheric Environment Service estimates of horizontal solar radiation at London, Ontario and converting them to values at a 60-degree tilt using the method recommended by Hay [11]. The effect of the reflector was included by assuming a constant ground albedo of 50 percent. The curves match closely except for May and June 1982. It would appear that these months were cloudier than normal. The total solar radiation measured at the site is 10 % below the long-term London average.

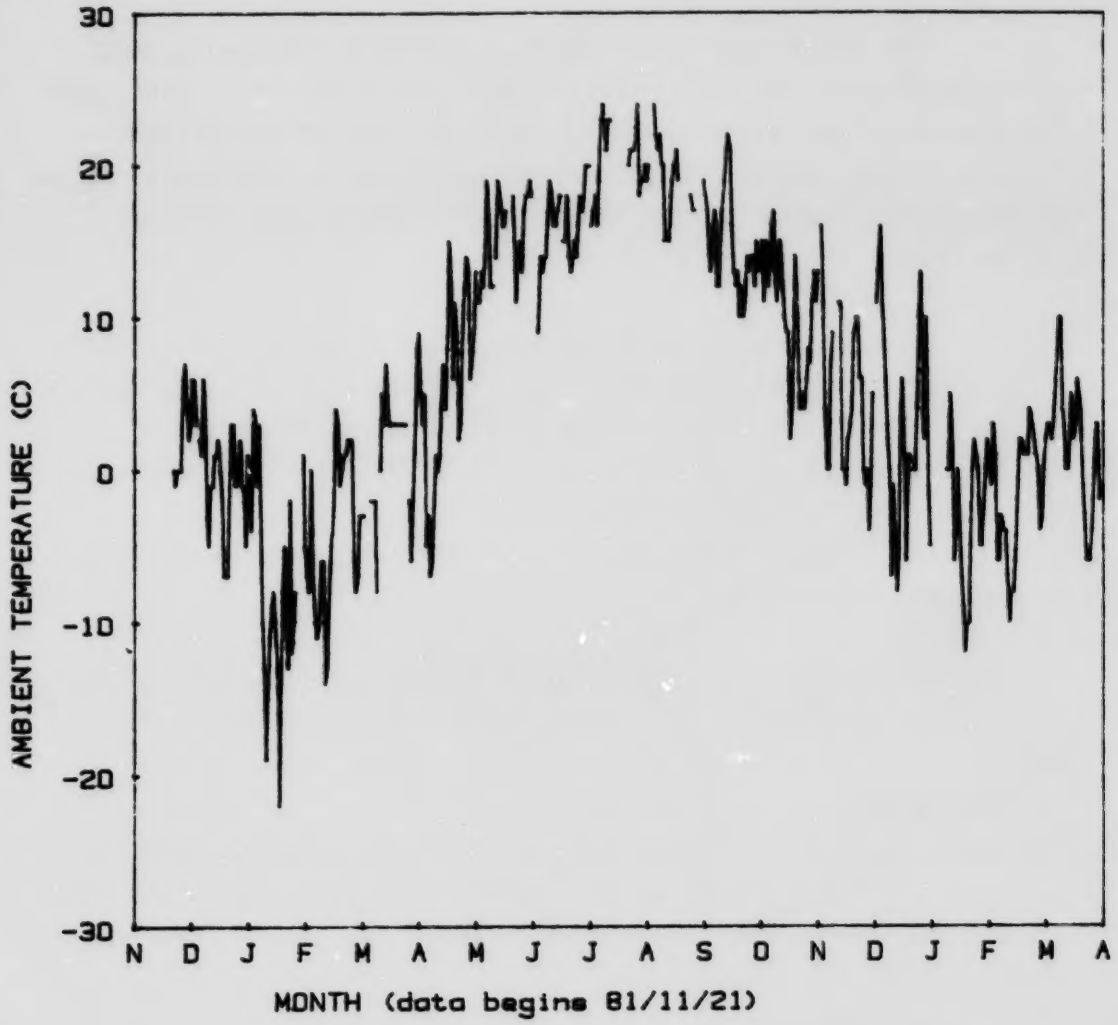

Figure 2.1 Daily Average Values of Ambient Temperature

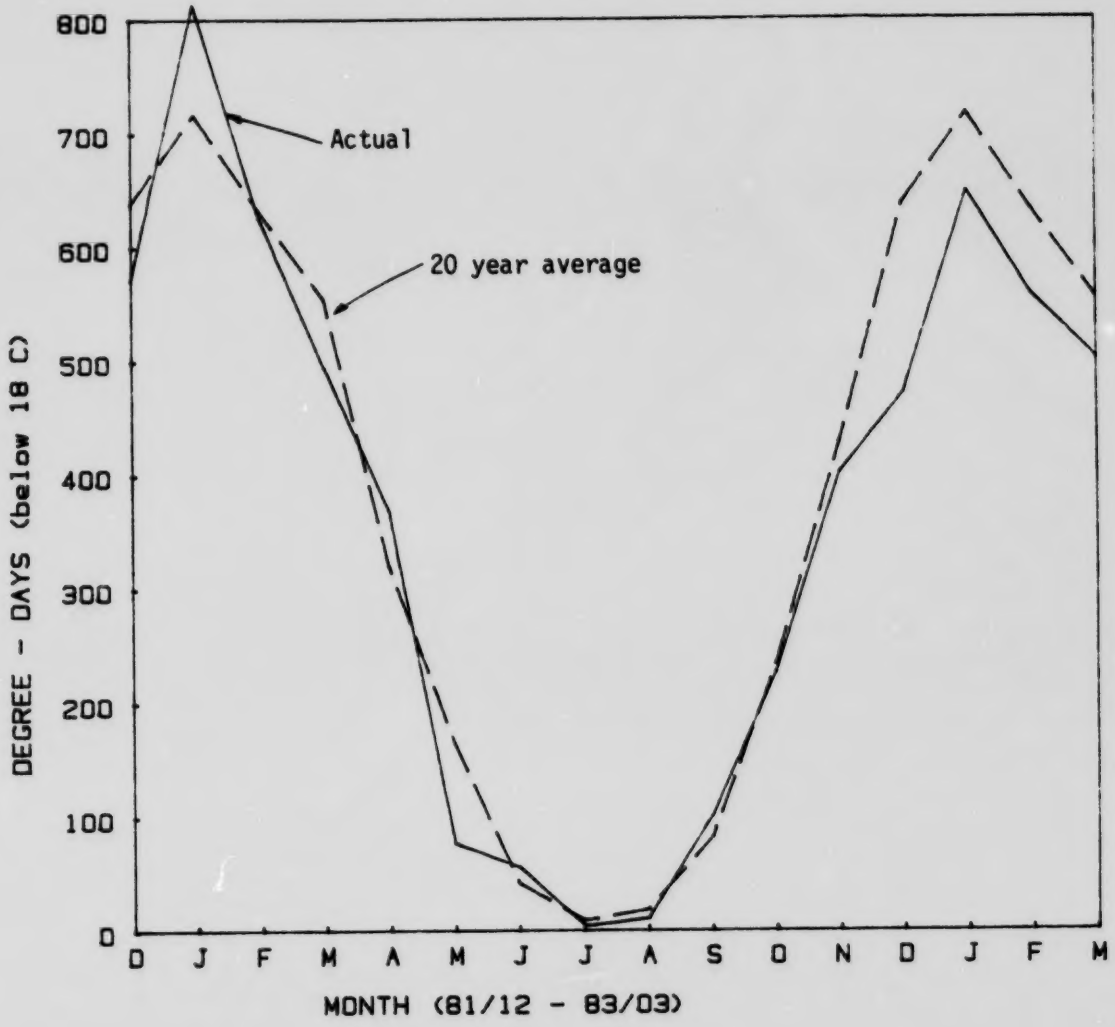

Figure 2.2 Number of Degree Days below 18°C

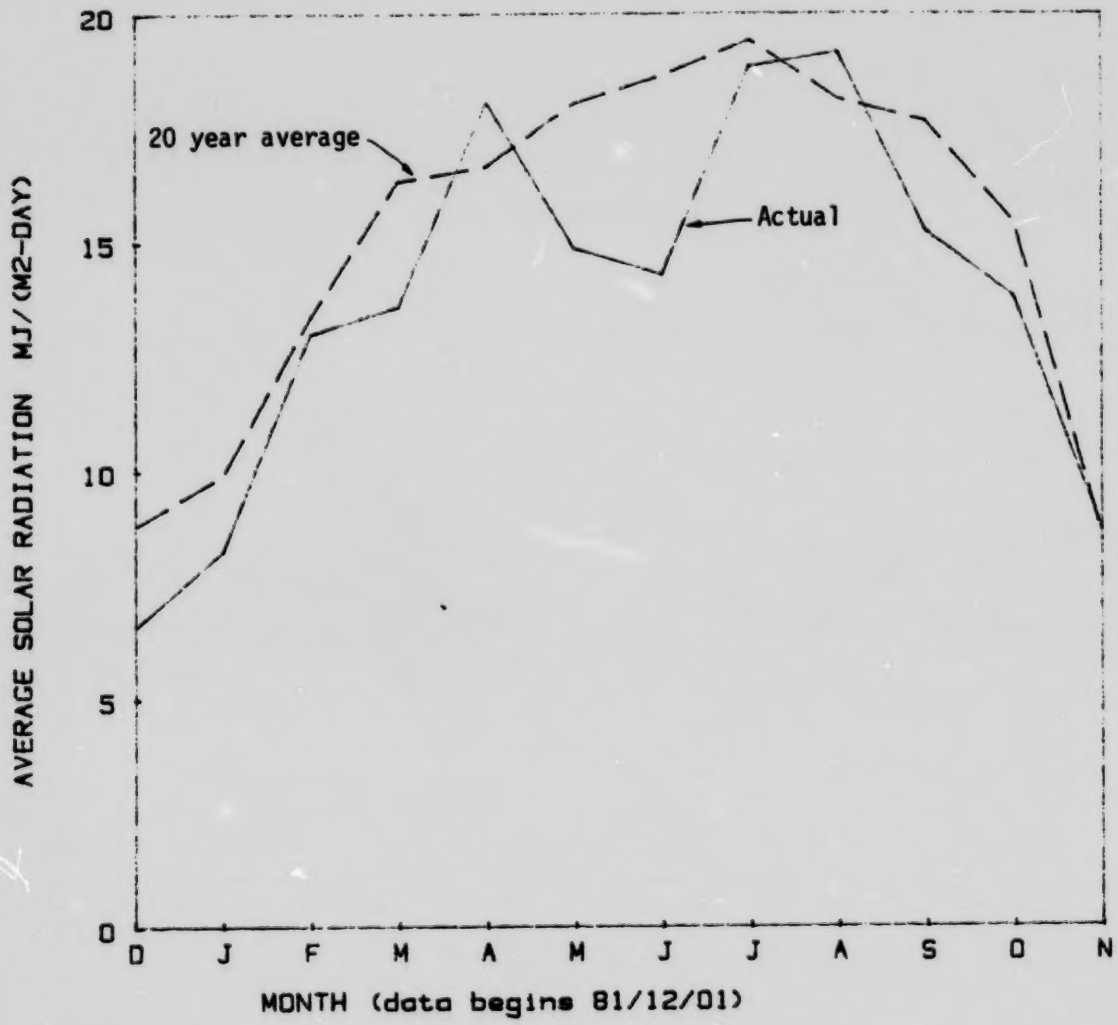

Figure 2.3 Monthly Values of Solar Radiation on a Surface Inclined 60°

3. PERFORMANCE OF THE BUILDING SYSTEMS

3.1 The Building Shell

3.1.1 Internal Heat Gains

Daily totals of internal heat gains (excluding solar heat gains) are presented in Figure 3.1. The figure shows that the internal gains are relatively constant at approximately 1150 MJ per day or 7.5 Watts per square metre of floor area. The minimum internal gains occur in May when the daylight period is longest. There are two peaks in the internal gains: Winter, 1982 and June/July, 1982. The high winter internal gains are probably due to increased lighting requirements and use of portable electric heaters. Upon completion of the building, the occupants were issued with portable 1500 Watt electric heaters. These heaters were removed in October 1982. The low internal heat gains during the 82-83 winter are probably a result of the elimination of the portable heaters. The peak summer internal heat gains are caused by window air conditioners installed on several of the units.

3.1.2 Building Heat Loss Coefficient

The Aylmer Senior Citizens' Residence was designed to be an energy conserving building (see Section 1.2.1 for description). The heat losses through the building shell are the driving force for several of the other systems.

Building heat loss is normally characterized by the heat loss coefficient (UA), that is the building heat loss (Q_{loss}) divided by the inside-to-outside temperature difference ($T_i - T_o$).

$$UA = \frac{Q_{loss}}{(T_i - T_o)} = \frac{Q_{heat} + Q_{ig}}{(T_i - T_o)} \qquad (3.1)$$

The building heat loss, however, was not measured.

By conservation of energy the heat loss must equal the heat gain. The heat gain is the total of the heat supplied by the heating system (Q_{heat}) and internal heat gain due to lights, appliances, people and solar radiation (Q_{ig}). The formulae for determining these and the other quantities used in Section 3 are given in Appendix C.

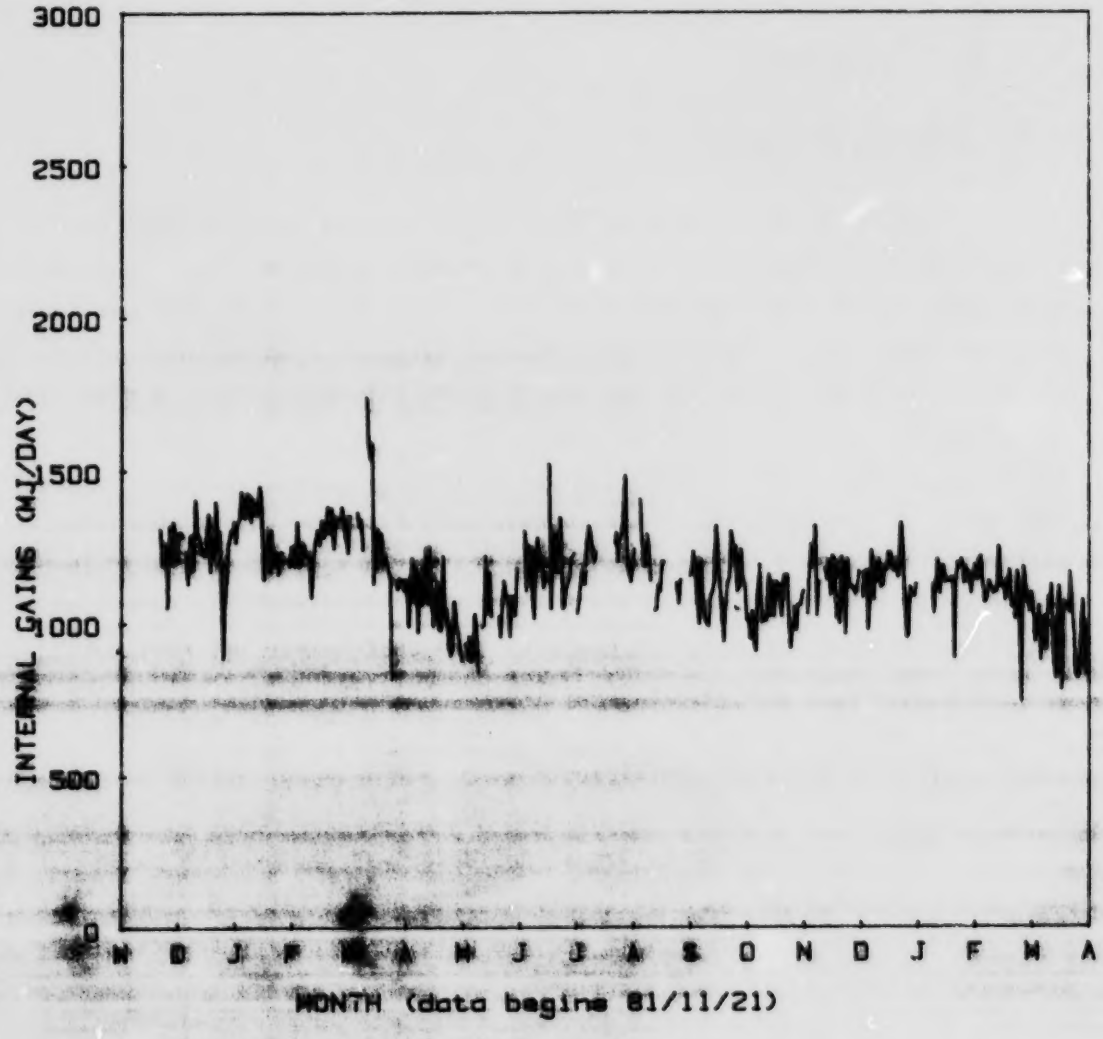

Figure 3.1 Daily Totals of Internal Heat Gains

To estimate the building heat loss coefficient requires an estimate of the indoor-to-outdoor temperature difference. The outdoor or ambient temperature was measured at the site. The average indoor temperature, however, was not measured directly. In six of the units the air temperature near floor level on the inside surface of an exterior wall was measured. In addition, the temperature of the air being exhausted from the units was measured. The air grills for the exhaust air are located near ceiling level. The true indoor air temperature is probably somewhere between these two extremes.

An examination of the data showed that on average the winter exhaust air temperature was six Celcius degrees warmer than wall temperature. (Because of monitoring problems, the exhaust air temperature was available for only a few months.) While this difference seems large, the wall temperature sensor may read low because it is directly below the bedroom window. Some of the occupants leave their bedroom window open during the winter. Cold air from the window would blow across the sensor, yielding a temperature reading lower than the average room temperature.

Plots of the building heat loss coefficient were made assuming the average indoor temperature was three degrees and six degrees warmer than the wall temperature (see Figures 3.2 and 3.3). The plot assuming a six degree temperature difference gives a more uniform value of heat loss coefficient and thus is assumed to be closer to the actual value. The low heat loss coefficient in January/February 1982 corresponds to the coldest period (see Figure 2.1). The low value of the heat loss coefficient could result from the inability of the heating system to supply enough heat or from a tendency for the occupants to close their windows on very cold days. Conversely, the high values calculated for other parts of the year (when the heating load is smaller) may be a result of less than 100% utilization of solar and internal gains. The calculation of heat loss coefficient assumes all solar and internal gains are used to meet the heating load.

The average building heat loss from Figure 3.3 is approximately 115 MJ/(day-°C) or 1330 W/°C. This is approximately 15% above the design value (see Section 1.2.1). Given the wide range in quality of building construction practices, the values are very close. Part of the reason for the higher measured value is the non-use of the storm windows and the increased infiltration due to open windows (see Section 1.2.1). Building ventilation is discussed in more detail in Section 3.6.

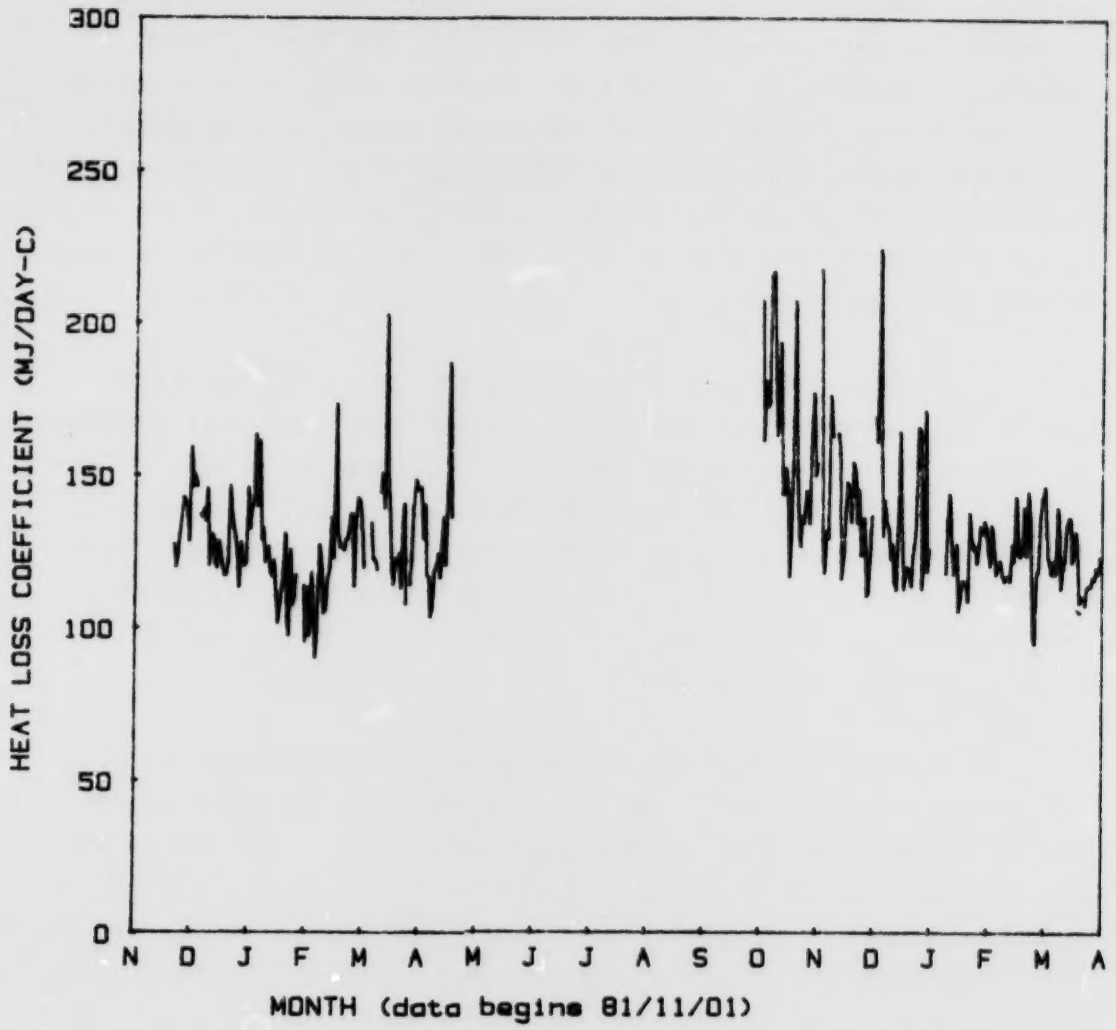

Figure 3.2 Building Heat Loss Coefficient Assuming Air Temperature 3°C Warmer Than Wall Temperature

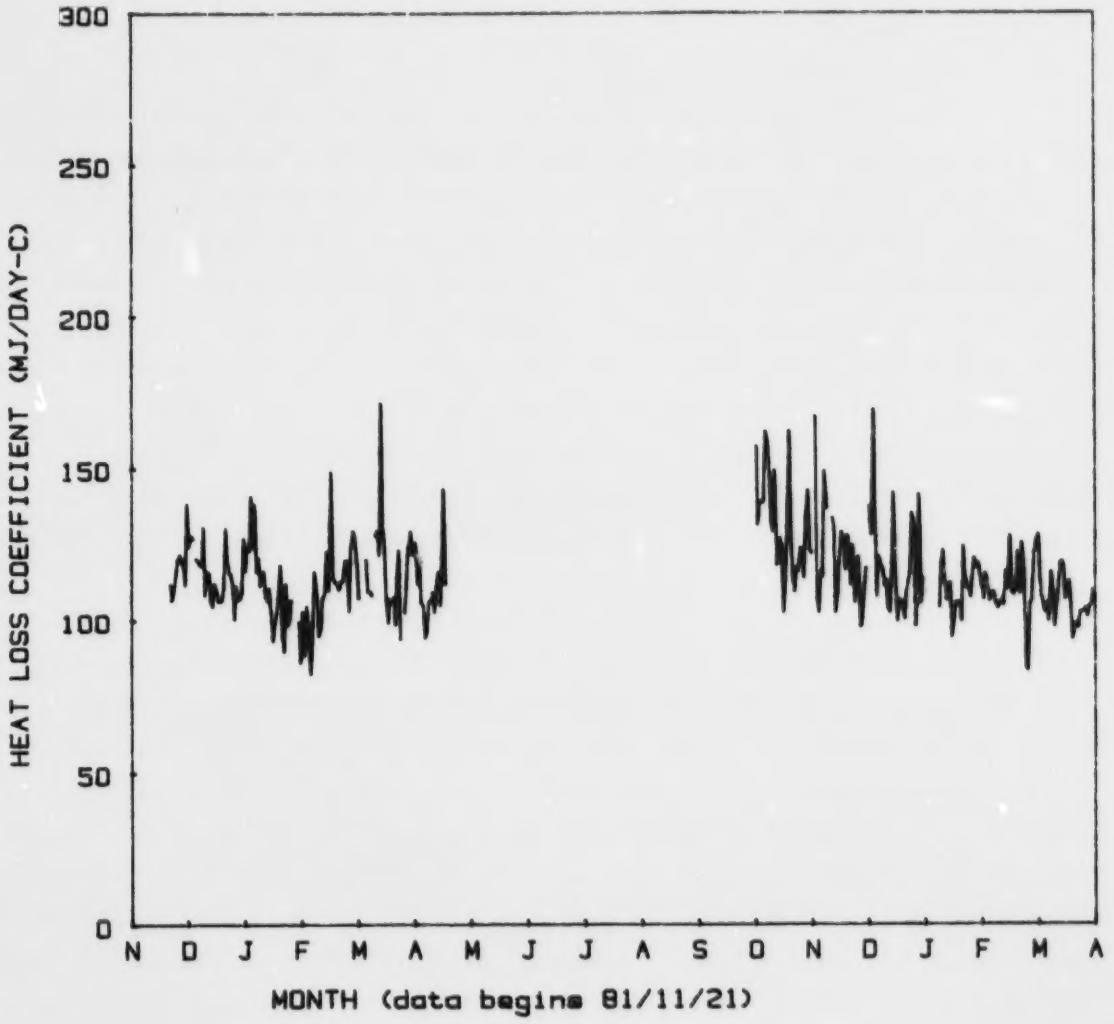

Figure 3.3 Building Heat Loss Coefficient Assuming Air Temperature 6°C Warmer Than Wall Temperature

3.2 Solar Collection System

3.2.1 Overview

The solar collection system was designed to collect solar energy year round to meet space and water heating loads. Table 3.1 presents monthly totals for solar energy collected for the period December 1, 1981 to November 30, 1982. According to the design report [10] annual solar heat collection should average 384 GJ. (The monthly values were not in the design report. These values were generated using the ENERPUB computer program and the weather data measured at the site for this period.) The actual amount collected over this period was 223 GJ (58% of design). This value is misleading because the system was shut down for two-and-a-half months because four collectors froze (see Section 1.2.2) and the system was operating without these collectors for an additional three-and-a-half months.

The adjusted solar heat collected values are an estimate of how much heat would have been collected had the collectors functioned all year. The values for January through March were determined by computer simulation using the site measured weather data, collector characteristics and heating loads (see Section 3.7 for a more complete description). The values for April to mid-July were increased by 2.6% to account for energy not collected because four of the 112 collectors were not operating. This factor was determined by comparing computer simulated results for this period for the two different collector areas. No additional correction was assumed necessary for this period because of the additional heat collected in January through March since this energy would have been used immediately for space heating and not for raising the tank temperature. The adjusted energy heat collection is 291 GJ or 76% of design. This corresponds to an annual heat collection rate of 1.58 GJ per square metre of aperture area.

The lower then expected performance is due to five factors, four of which are related to the solar collection system: smaller (than design) collector area, poorer (than design) collector performance, array flow distribution and collector control problems. These factors are addressed in Sections 3.2.2 and 3.2.3.

Table 3.1: Solar Energy Collected in GJ

December 1, 1981 - November 30, 1982

	Projected	Measured	Adjusted
D	12.56	10.68	10.68
J	15.95	4.88	12.02
F	38.15	-	26.66
M	45.86	-	31.96
A	59.93	45.65	46.84
M	39.25	31.85	32.68
J	31.68	21.06	21.61
J	45.18	33.16	33.60
A	35.70	28.56	28.56
S	25.39	18.74	18.74
O	26.36	20.30	20.30
N	11.67	7.69	7.69
	387.00	222.61	291.30

The fifth factor is the heat delivery system. Heat delivery affects solar heat collection in that it changes the temperature of the storage tank. A lower storage tank temperature means a lower collector inlet temperature and higher collector efficiency. Potential improvements in solar heating system performance due to changes in heating system operation are discussed in Section 3.7.

3.2.2 The Collectors

As discussed in Section 1.2.2, the collector array collected less energy than the design value because the area of solar collectors installed was 16% less than the design value.

The lower than expected performance of the collector array is also due to differences in the collector efficiency curve. Figure 3.4 shows three collector efficiency curves. The top line marked "initial test result" is the curve on which the design values were based.[1] Subsequent to the design report, the collector was retested. The resulting efficiency curve is shown in Figure 3.4 marked "second test result". It is difficult to determine why the second test result is so much lower than the initial test. Possible explanations include differences in testing agencies and test procedures, variation in collector quality and changes in collector material suppliers or design. The third line on Figure 3.4 is the on-site collector performance as determined from the monitoring data.

The seasonal performance of the collector array is shown in Figure 3.5. This figure shows monthly values of collector efficiency (solar energy collected divided by incident solar radiation). The efficiency shows a steady decrease from April to November. The main reason for the efficiency decrease is the increase in storage tank (i.e. collector inlet) temperature. A higher collector inlet temperature means that there are fewer hours that the solar radiation absorbed is greater than collector heat loss. For the period April to November the average collector efficiency is 30.4% (based on aperture area). Extrapolating for a full year (using computer simulation) the annual collector efficiency is 31.6% (based on aperture area).

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1 The collector efficiency curve in the design report was based on average collector temperature. This curve was revised to be based on collector fluid inlet temperature and system design flow rate using the method of Duffie and Beckman [7].

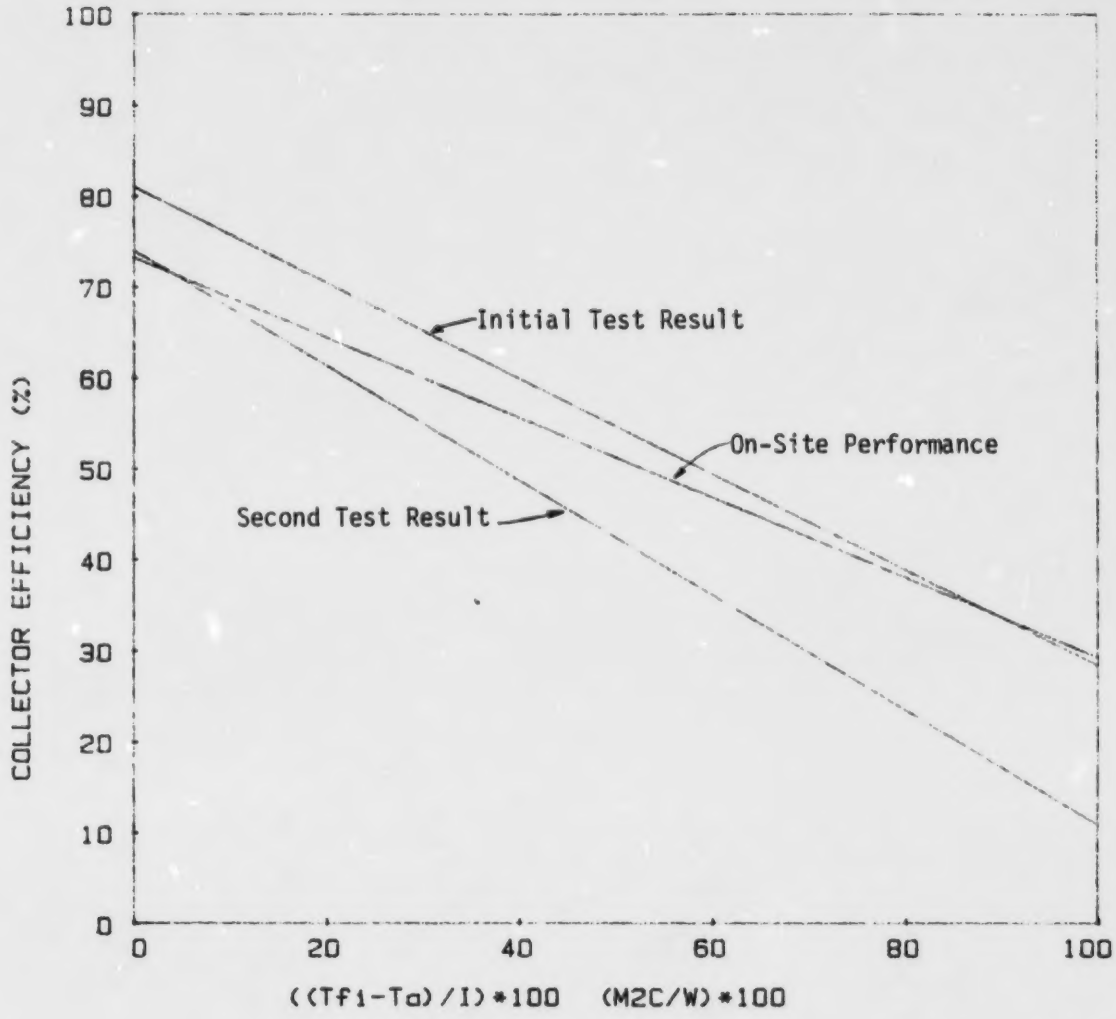


Figure 3.4 Instantaneous Collector Efficiency Curves

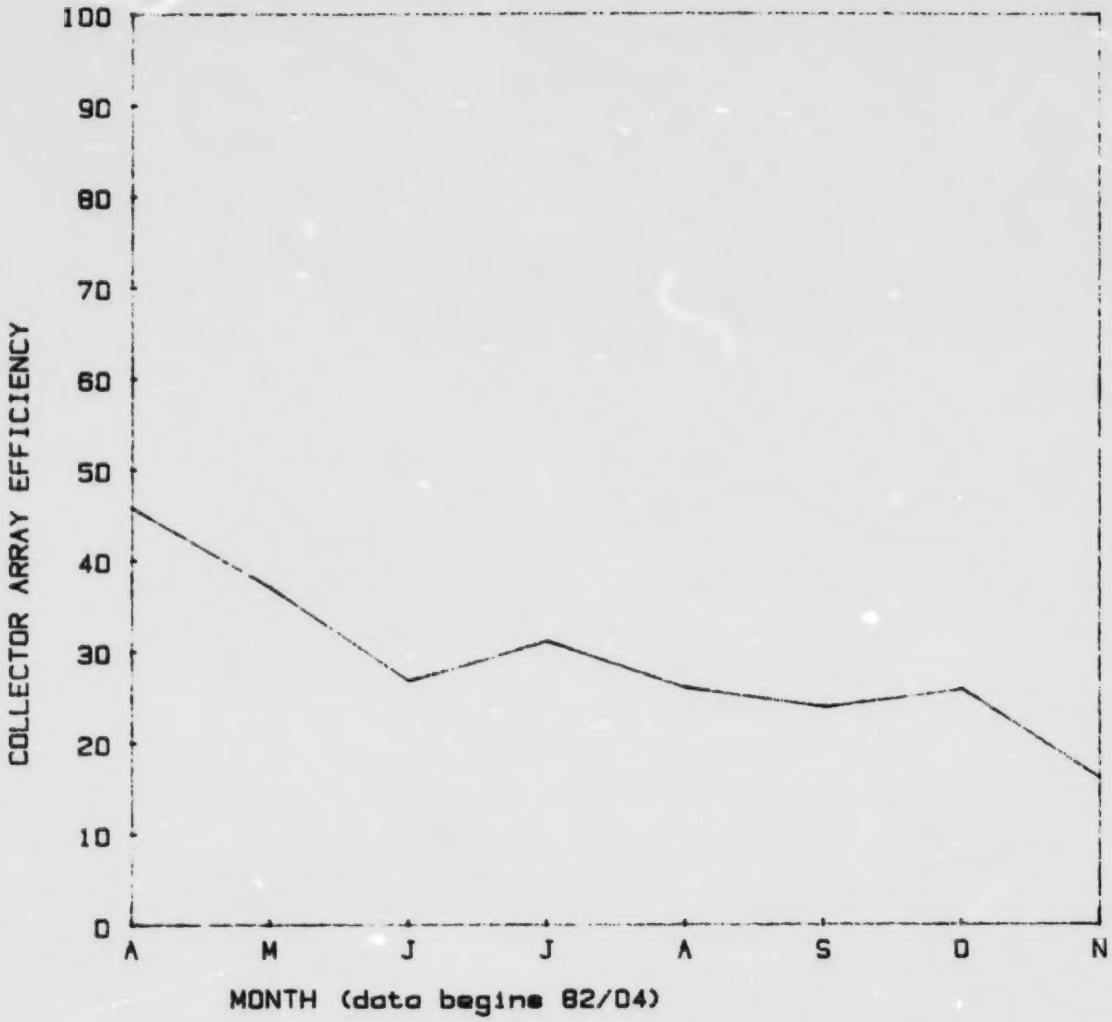


Figure 3.5 Monthly Collector Array Efficiency

The reduction in heat collection due to the smaller collector area and lower collector efficiency curve was estimated using computer simulation. These two factors reduce heat collection by 32 GJ or approximately 8%. While this reduction may seem small relative to the differences in collector area, it should be remembered that, because of the law of diminishing returns, the extra collectors are the least efficient since they are used to raise the tank temperature above 75 °C.

3.2.3 Collector Operation

Collector performance can be lower than expected if the collector fluid flow to each pair of collectors is not equal. To check for flow imbalance, the temperature rise across four pairs of collectors was analysed. Assuming equal collector efficiencies, the temperature rise at any hour is inversely proportional to the flow rate. That is, the collector pair with the highest temperature rise has the lowest flow rate and vice versa. Figure 3.6 shows the average collector temperature rise for an eight-month period. In general collector pairs 1, 2 and 3 have similar temperature rises. Collector pair 4, however, generally has a higher temperature rise. The reduced temperature rise in September and October is probably because of the low collector efficiency during this period of high storage tank temperature.

Figure 3.7 shows the temperature rise across the collectors for a sunny day in October. It is important to note that in early morning and late afternoon there can be a negative temperature rise. This indicates that there may be control problems.

It is difficult to estimate the loss in solar heat collection due to flow imbalance and control problems. It is felt, however, that these factors are not a major contributor to the loss in performance. After accounting for differences in collector area and performance characteristics, the lower monitored performance is due to heat delivery system operation (i.e. no solar heat can be delivered to the DHW load during the summer and, during the winter, solar heat and the electric boiler are used each day in order to use solar heat more uniformly throughout the winter, see Section 3.7).

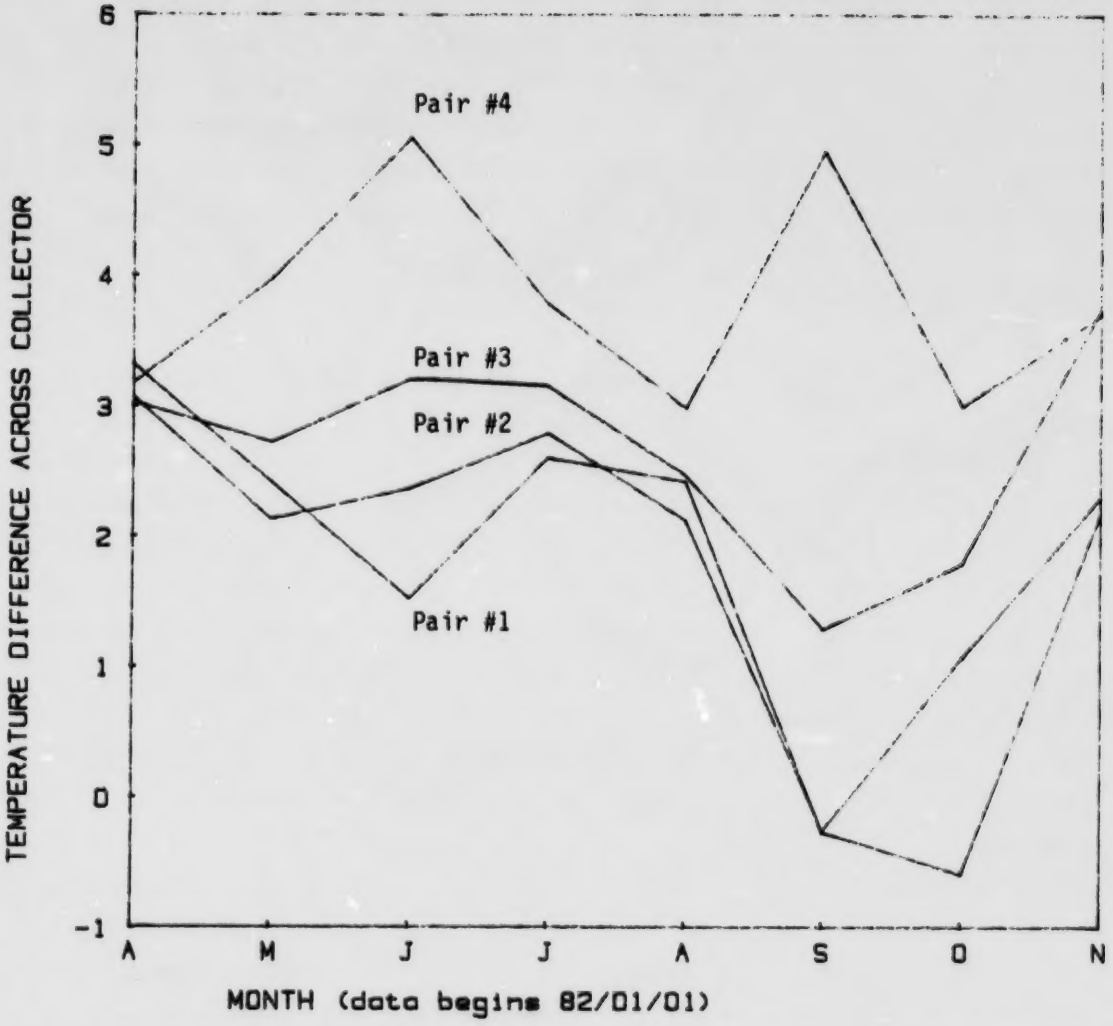


Figure 3.6 Monthly Average Temperature Rise Across Pairs of Collectors in Celsius Degrees

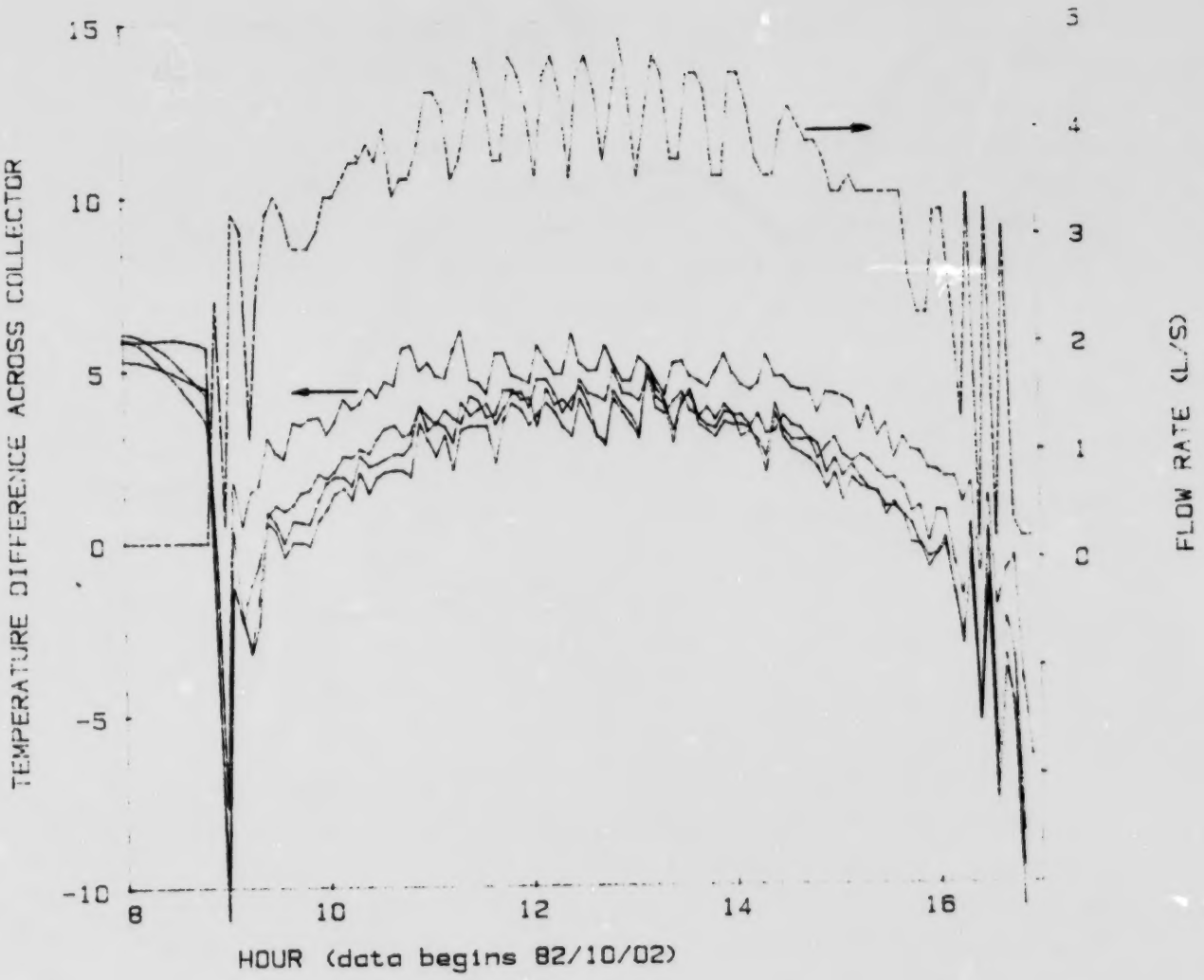


Figure 3.7 Collector Flow Rate and Temperature Rise for a Typical Sunny Day

3.2.4 The Reflector

Unfortunately, because of measurement problems with one of the pyranometers (R1) the contribution of the reflector can only be examined for the period December 1981 to June 1981. For this period, the ratio of solar radiation received at the centre of the array to the solar radiation received at the same angle but away from the reflector is shown in Figure 3.8. The amount that this ratio is greater than unity is due to the reflector. The figure shows that on average the solar radiation is increased by 8% because of the reflector. The contribution of the reflector appears to be higher in the summer than in the winter. While at first this may seem confusing, it is to be expected. During the winter the sun is at a very low angle in the sky, thus very little solar radiation will strike the reflector. In the summer the sun is almost normal to the reflector; because the reflector produces a diffuse reflection (as opposed to specular) much of the summer sun will be reflected onto the collectors.

3.3 Solar Storage Tank

3.3.1 Tank Temperature

The solar storage tank was designed for annual heat storage, that is, heat collected during the summer would be stored for use in winter. Figure 3.9 shows daily values of average storage tank temperature. For the period November 1981 to November 1982, the average tank temperature was calculated using two sensors, while for the remainder of the period the temperature was calculated using 9 sensors.

The yearly fluctuation in tank temperature is very close to the design predictions of 29°C to 75°C. The change in slope of the graph in mid-January is a result of shutting off the solar heat delivery system. It should be remembered, however, that the system cannot supply heat to the summer DHW load and solar heat and electric heat are often both used daily during the winter. Both of these factors contribute to a high tank temperature.

To achieve maximum performance it is desirable to have the storage tank temperature stratified (warm water at the top for heat delivery, cold water at the bottom for heat collection). Because of malfunctioning sensors, stratification was examined only during the period November 1982 to March 1983. Figure 3.10 shows the daily average temperature of the tank centreline

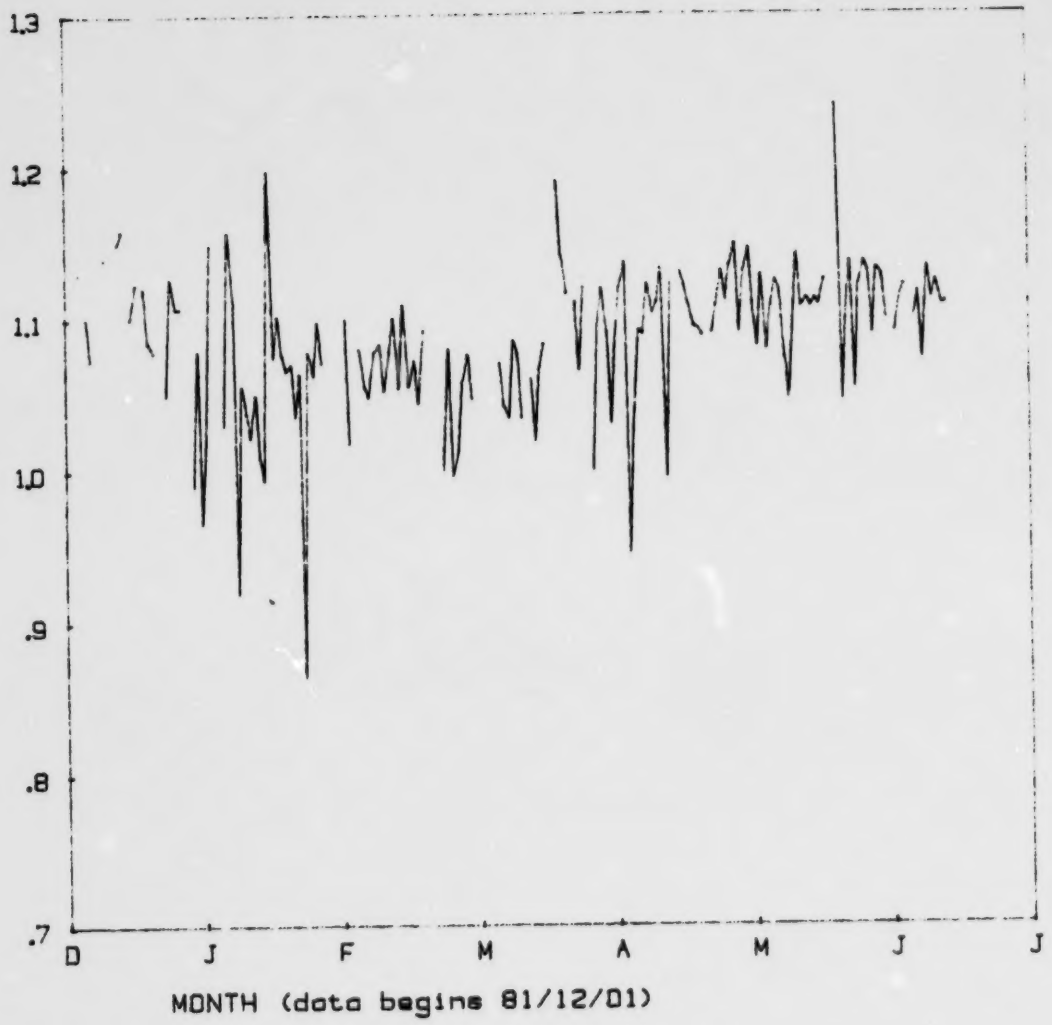


Figure 3.8 Effect of Reflector on Solar Radiation Intensity

(Ratio of Solar Radiation received at the centre of the array to that received away from the reflector)

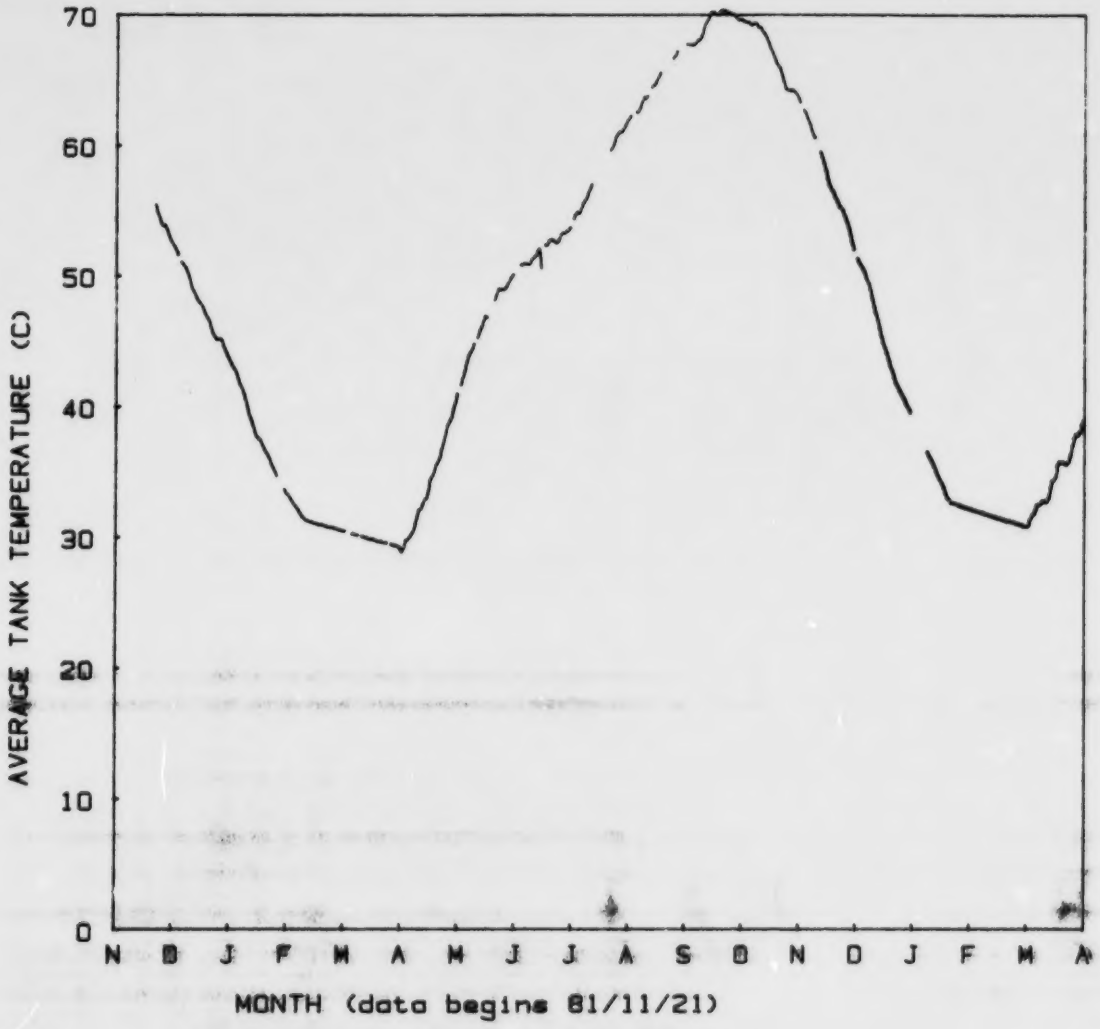


Figure 3.9 Daily Solar Storage Tank Temperatures

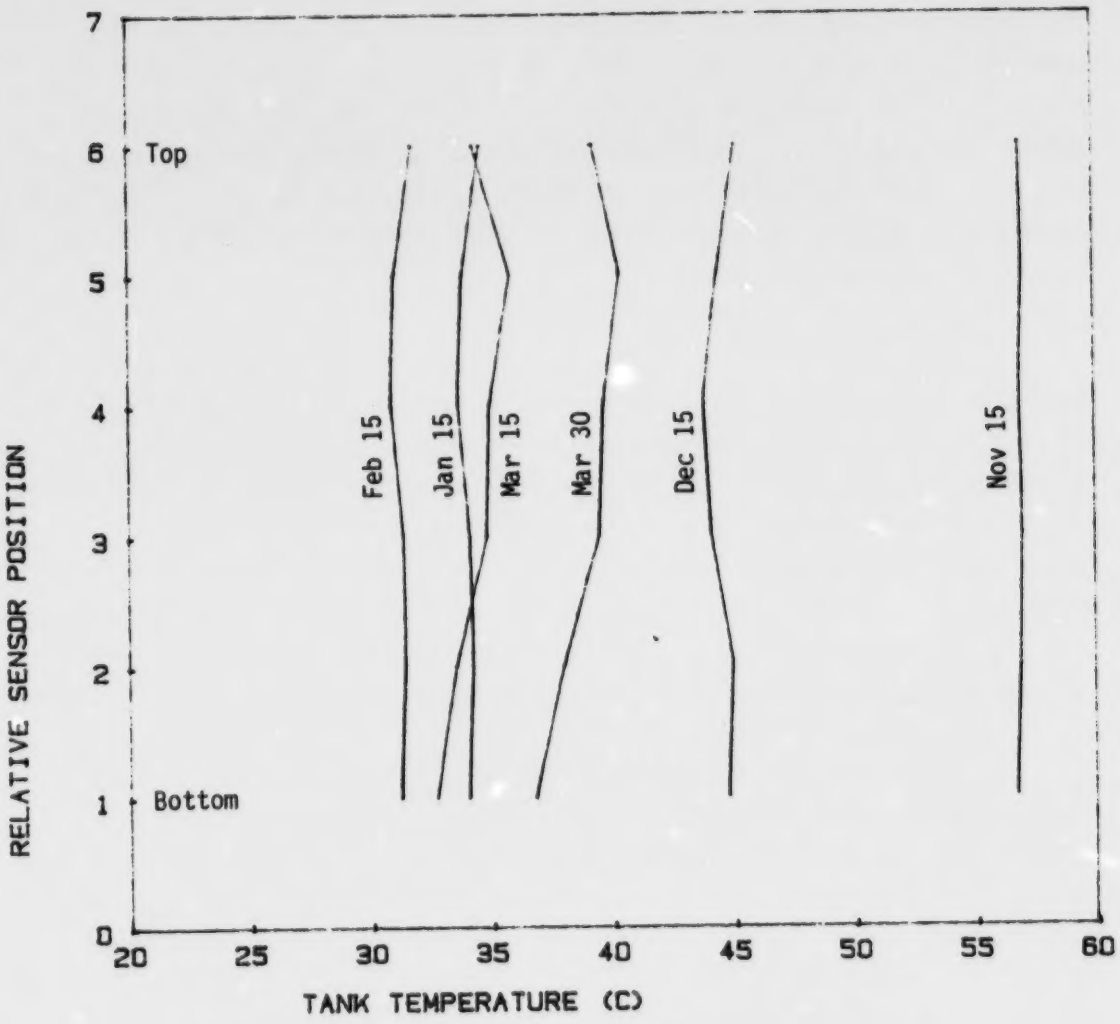


Figure 3.10 Stratification in Solar Storage Tank

where one is the bottom of the tank and six is the water surface. During the period when the heat delivery system is operating (November 15 to January 15) there is very little tank stratification. This is probably a result of the location of the pipe connections. The heat delivery supply and return pipe connections are located at the top of the tank. Thus cool water returning from the heating system is injected into the tank above warmer water. Density differences will cause the tank water to mix to a uniform temperature.

When heat delivery is shut off and the solar collection system is operating (March 15 and 30), tank stratification of approximately four Celcius degrees occurs. The magnitude of the stratification is limited by the temperature rise across the collectors, which in turn is dependent on the collector flow rate. Figure 3.6 shows that the average collector temperature rise is approximately three to four Celcius degrees at a flow rate of 1.8 litres/min per square metre of collector. Stratification could be increased by slowing down the flow rate to a more typical value of approximately 0.5 litres/min per square metre of collector.

There are several possible reasons why the top of the tank is cooler than the rest of the tank. The water may be cooler because of evaporative cooling to the air or because the return water from the collectors is cooler in late afternoon than at midday. Alternatively the sensor may be out of the water (measuring air temperature) or out of calibration.

Temperature variation in the horizontal direction was also analysed. It was found that the water temperature at the tank edge was less than one Celcius degree cooler than water at the centreline.

3.3.2 Tank Heat Loss

The total tank heat loss for 1982 was 51.6 GJ. This is approximately half the value given in the design value of 110 GJ. There are two possible reasons for the reduced heat loss: higher insulation levels and lower temperatures. Dillon in their investigation of the tank noted that the tank insulation was sprayed on in uneven thicknesses ranging from 125 to 305 mm. Thus, it is possible that the average insulation thickness is greater than the design value of 150 mm. Because of the lower than expected heat collection, the tank temperatures were slightly lower

than the values used for design purposes (maximum design temperature 75°C, actual maximum temperature 70°C).

An accurate assessment of the monthly tank heat loss is difficult to determine because of the large tank volume and small heat loss. The amount of heat lost by the tank over a day represents a 0.04 Celcius degree change in tank temperature. It is difficult for the monitoring system to detect this change in mean tank temperature.

Monthly values of tank heat loss coefficient had variations of over 100% with an average value of 40 W/°C. Alternatively the tank heat loss coefficient could be estimated for the periods when the tank was isolated from the heat delivery and heat collection systems. The tank was isolated for 49 days in February-March, 1982 and for 39 days in January-February, 1983. The tank heat loss can be determined by observing the temperature decay over these periods. The average tank heat loss was 1870 Watts and 2000 Watts for 1982 and 1983 respectively. Assuming that the heat loss is to the average of the air and ground temperatures, the tank heat loss coefficient is 69 W/°C. The design heat loss can be calculated to be approximately 83 W/°C. Thus the actual heat loss coefficient is 17% less than the design estimate.

3.4 Heat Delivery System

3.4.1 Space Heating Load

Projected and actual space heating loads are shown in Table 3.2 The space heating load is 20% higher than the projected load. The main reasons for this increase are a higher indoor air temperature and higher heat losses because of open windows (see Section 3.1).

3.4.2 Solar Heat Delivery

It is difficult to analyse solar heat delivery to space in isolation. Solar heat collected must be delivered to either the space or domestic hot water or be lost from the tank. Increasing one of these components means that the others must decrease. Table 3.3 shows the actual distribution of the solar heat. Tank heat loss is discussed in Section 3.3 and solar heat delivery to DHW is discussed in Section 3.5.

Table 3.2 Space Heating Loads (in GJ)

December 1, 1981 to November 30, 1982

	Space Projected	Space Actual
D	37.58	44.39
J	55.74	54.78
F	40.25	43.68
M	33.12	39.11
A	20.54	30.87
M	2.95	4.15
J	2.85	0.
J	0.	0.
A	0.	0.
S	2.34	0.
O	8.90	25.76
N	22.73	35.10
Total	227.00	277.8

Table 3.3 : Actual Solar Heat Distribution in GJ

December 1, 1981 to November 30, 1982

	Solar Collected	Solar to Space	Solar to DHW	Tank Losses
D	10.68	29.78	8.46	4.24
J	4.88	31.96	6.09	.65
F	0.	5.75	1.53	1.82
M	0.	0.	0.	5.37
A	45.65	0.	0.	.52
M	31.85	.22	0.	3.06
J	21.06	0.	2.77	4.07
J	33.16	0.	0.	4.70
A	28.56	0.	0.	6.32
S	18.74	0.	0.	11.12
O	20.30	24.28	15.33	3.49
N	7.69	33.78	9.55	6.48
Total	222.6	125.8	43.7	51.6

Because of the higher than expected space and domestic hot water load and lower than expected solar heat collected, the solar heating system could not meet the full space heating load. Rather than use the solar heat for the first part of the winter and the electric boiler for the remainder of the winter, both solar and electric heating were used each day. Solar heat was used from 7 A.M. to 10 P.M. and the electric boiler was used during the night. The advantage of this method of operation is that electricity is used at off-peak periods. However, until Ontario has off-peak electrical rates, the cost of heating the building would probably be less by supplying solar heat continuously. This method of operation would result in a lower storage tank temperature and, thus, higher collector efficiencies (see Section 3.7).

The actual solar heat delivered to space is 125 GJ or 45% of the actual load and 55% of the design load. As was discussed in Section 3.2 this value is misleading because of the solar heat collection system was shut down for two and a half months to repair the damaged collectors. Table 3.4 presents adjusted values of solar heat distribution accounting for the additional heat that would be collected in a normal year. It is difficult to estimate where the additional solar heat would be delivered and what the monthly distribution would be. For this report, it has been assumed that the additional solar heat delivery would be divided between space heating, water heating and tank losses in the same proportions as they are for the actual solar heat delivery. These values are shown in Table 3.4. Using the adjusted value, the solar contribution to the space heating load is 165 GJ or 59% of the actual load or 73% of the design load.

Figure 3.11 shows the actual percentage of the space heating load met by solar heat. The solar heating system supplies close to 100% in the early winter, but falls to 65% in mid-winter and 0% in late winter. (The negative values are a result of a very small error in temperature measurement; there is no negative solar heat delivery). It is in the mid-winter period that the system daily alternates between solar and electric heat to extend the length of season that solar heat is supplied. The potential for improved solar heat delivery by using a different operating strategy is discussed in Section 3.7.

Table 3.4: Adjusted Solar Heat Distribution in GJ

December 1, 1981 to November 30, 1982

	Solar Collected	Solar Delivered to Space	Solar to DHW	Tank Losses
D	10.68	29.78	8.46	4.24
J	12.02	31.96	6.09	.65
F	26.66	↑	↑	↑
M	31.96	44.80	15.0	26.40
A	46.84	↓	↓	↓
M	32.68	↓	↓	↓
J	21.61	0.	2.77	4.07
J	33.60	0.	0.	4.70
A	28.56	0.	0.	6.32
S	18.74	0.	0.	11.12
O	20.30	24.28	15.33	3.49
N	7.69	33.78	9.55	6.48
Total	291.3	164.6	57.2	67.5

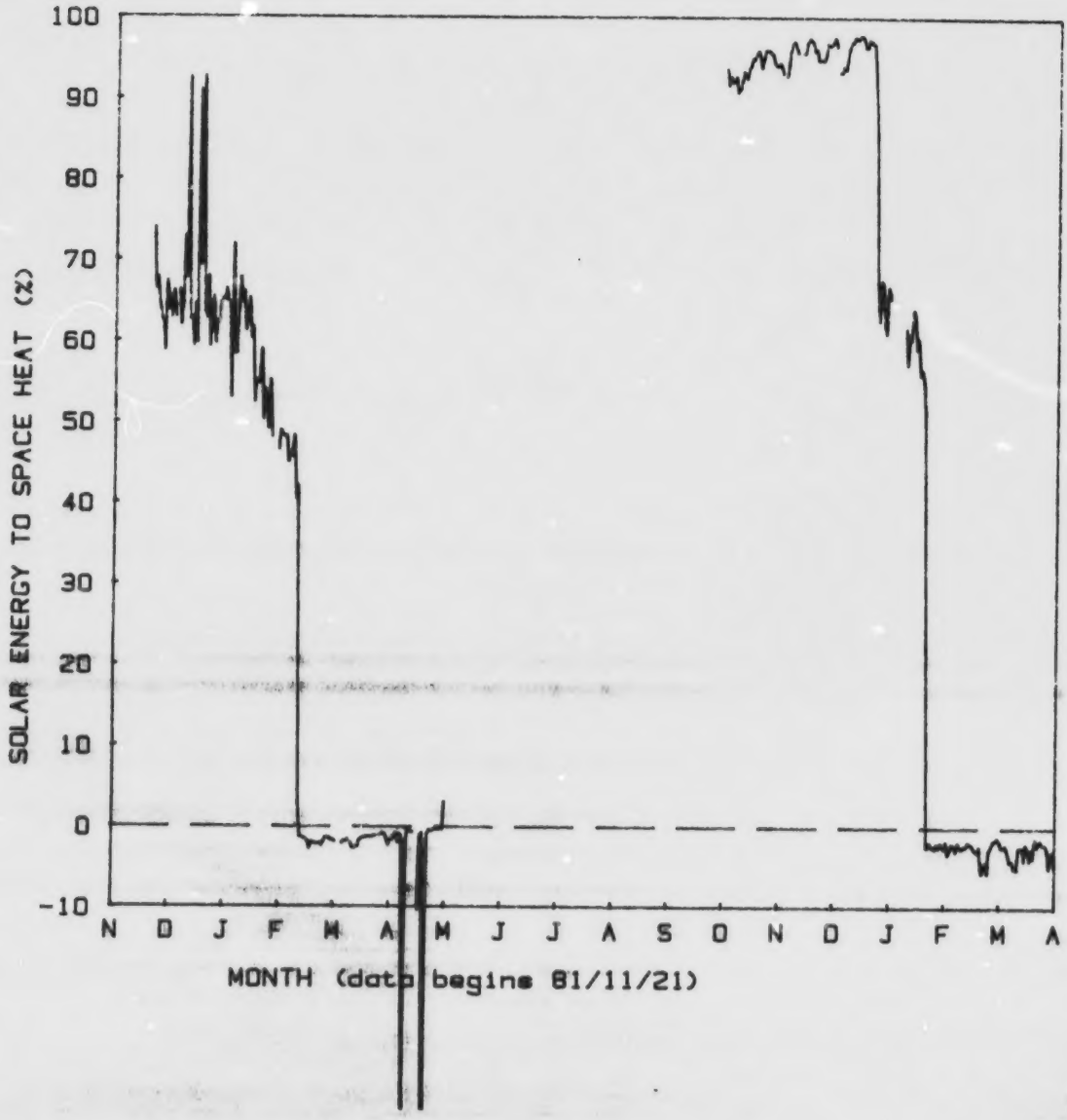


Figure 3.11 Daily Percentage Solar Contribution to the Space Heating Load

3.4.3 Thermal Comfort

While there are many ways to determine thermal comfort, the procedure used in this report is to examine air temperature at the exterior wall in the monitored units. Figures 3.12 and 3.13 shows these air temperatures over a 24 hour period for units on the south side of the building. Figures 3.14 and 3.15 show the results for the two units on the north side. November 25, 1981 was moderately sunny with an average ambient temperature of 1°C. February 2, 1982 was a very sunny day with an outdoor temperature of -7°C.

Because of higher solar gains, the south units experience a larger temperature swing than the north units. The maximum temperature swing for any unit is approximately 7 C°, an acceptable maximum value, with the peak occuring at 7 P.M. This temperature swing is probably due to a combination of solar gains and supper time internal gains. It is difficult to comment on the variations between units. It is possible that the low temperatures of Figures 3.13 are caused by open windows or by a lower thermostat setpoint. Figure 3.14 shows the change in air temperature when the window above the sensor is opened. Figure 3.15 shows the air temperature for a cold February day for north facing units. For this day, the air temperature at the exterior wall is relatively constant at 20°C or above. Thus, it would seem that the thermal comfort of the suites is acceptable.

3.5 Domestic Hot Water System

3.5.1 Hot Water Load

The projected and actual values of hot water load are presented in Table 3.5. Because of monitoring problems, there is no measured data for March through September 1982. It was assumed that the daily hot water consumption for this period was equal to the average hot water consumption when the monitoring system was operational. Actual energy consumption is almost three times the projected value and close to the amount of energy used for space heating. Measured average hot water usage is 2250 litres per day or 68 litres per day per person. This is consistent with the ASHRAE recommended average hot water consumption of 50 to 70 litres per day per person for nursing homes and dormitories. It would appear that the design energy consumption was underestimated.

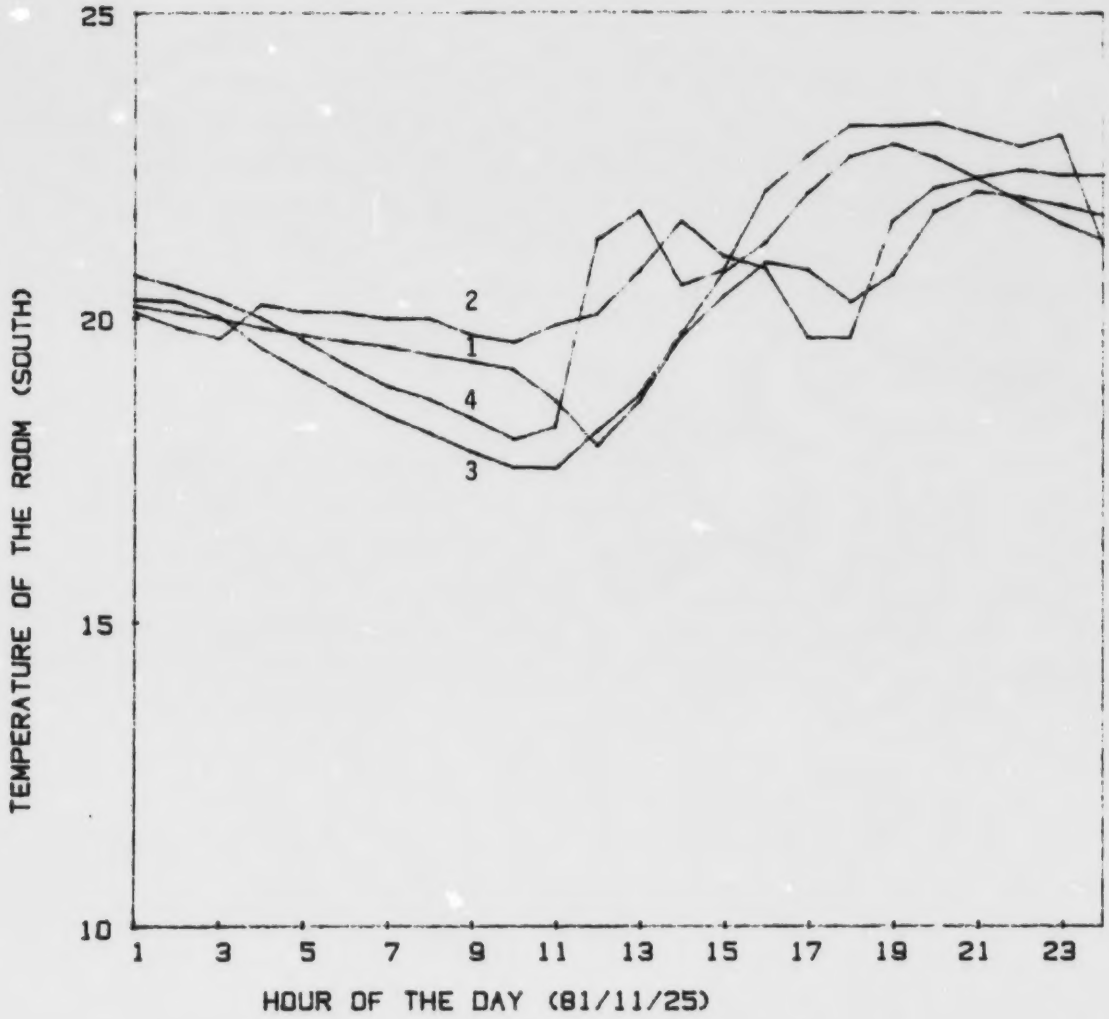
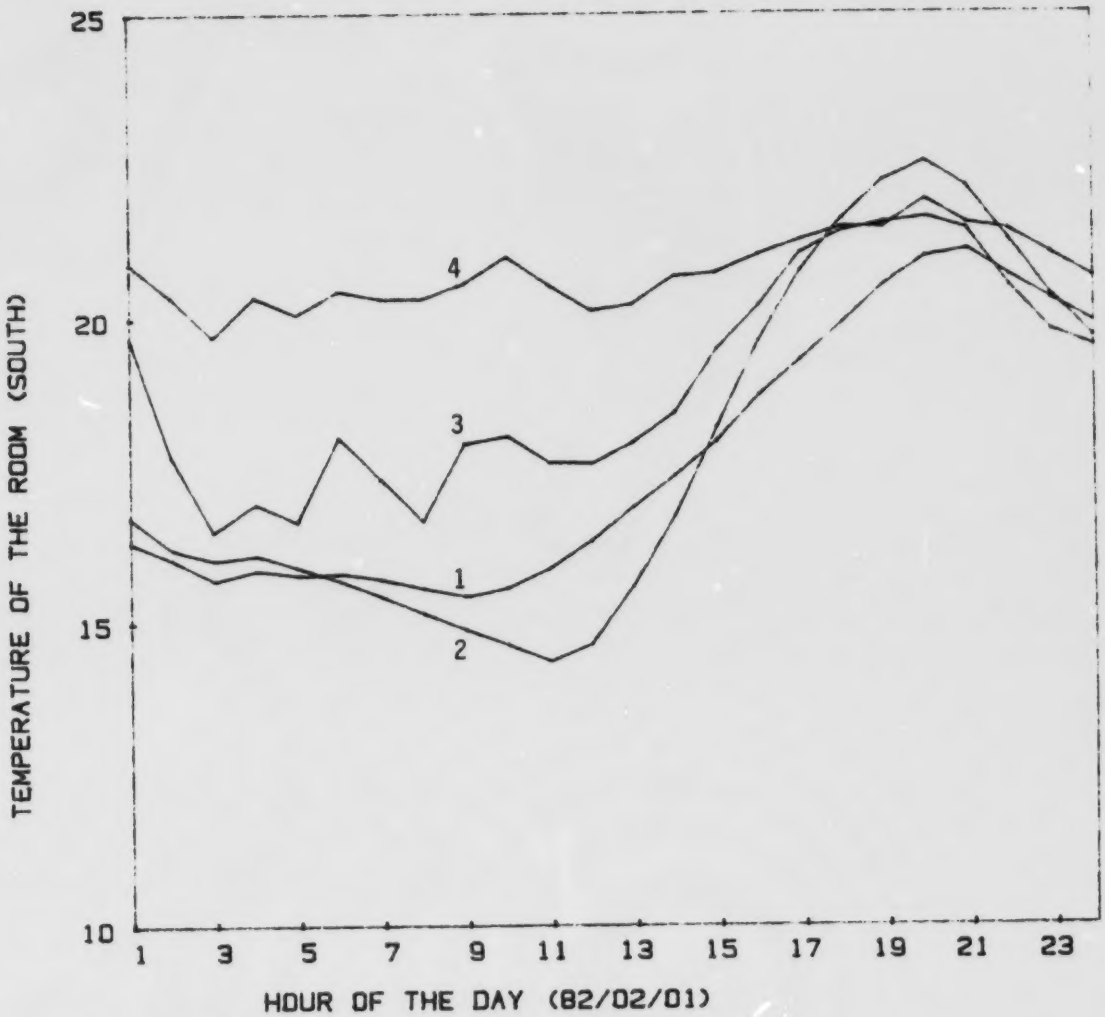


Figure 3.12 Hourly Values of Room Air Temperature - South Side



Where 1 is Unit #105
2 is Unit #115
3 is Unit #207
4 is Unit #216

Figure 3.13 Hourly Values of Room Air Temperature - South Side

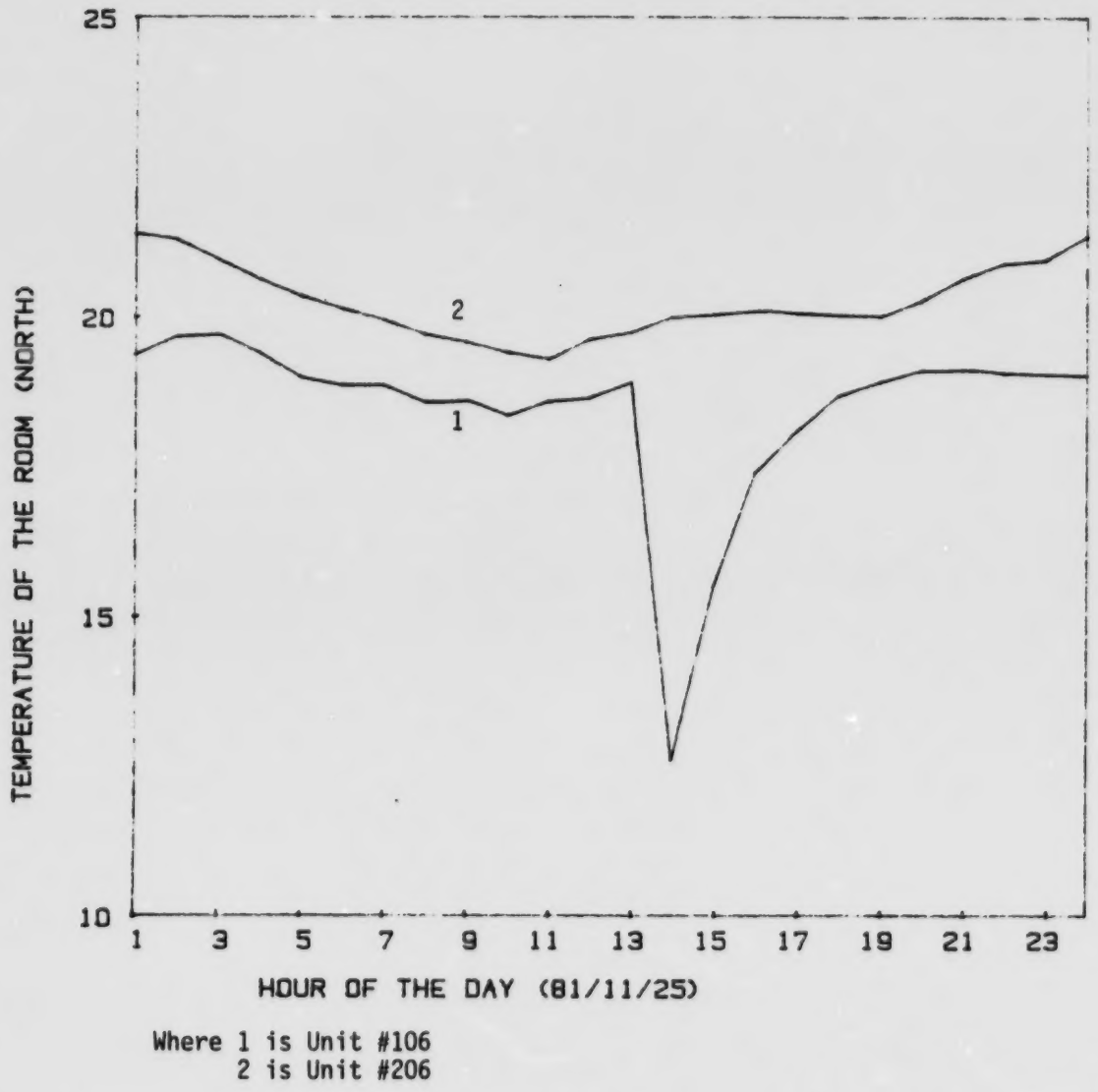


Figure 3.14 Hourly Values of Room Air Temperature - North Side

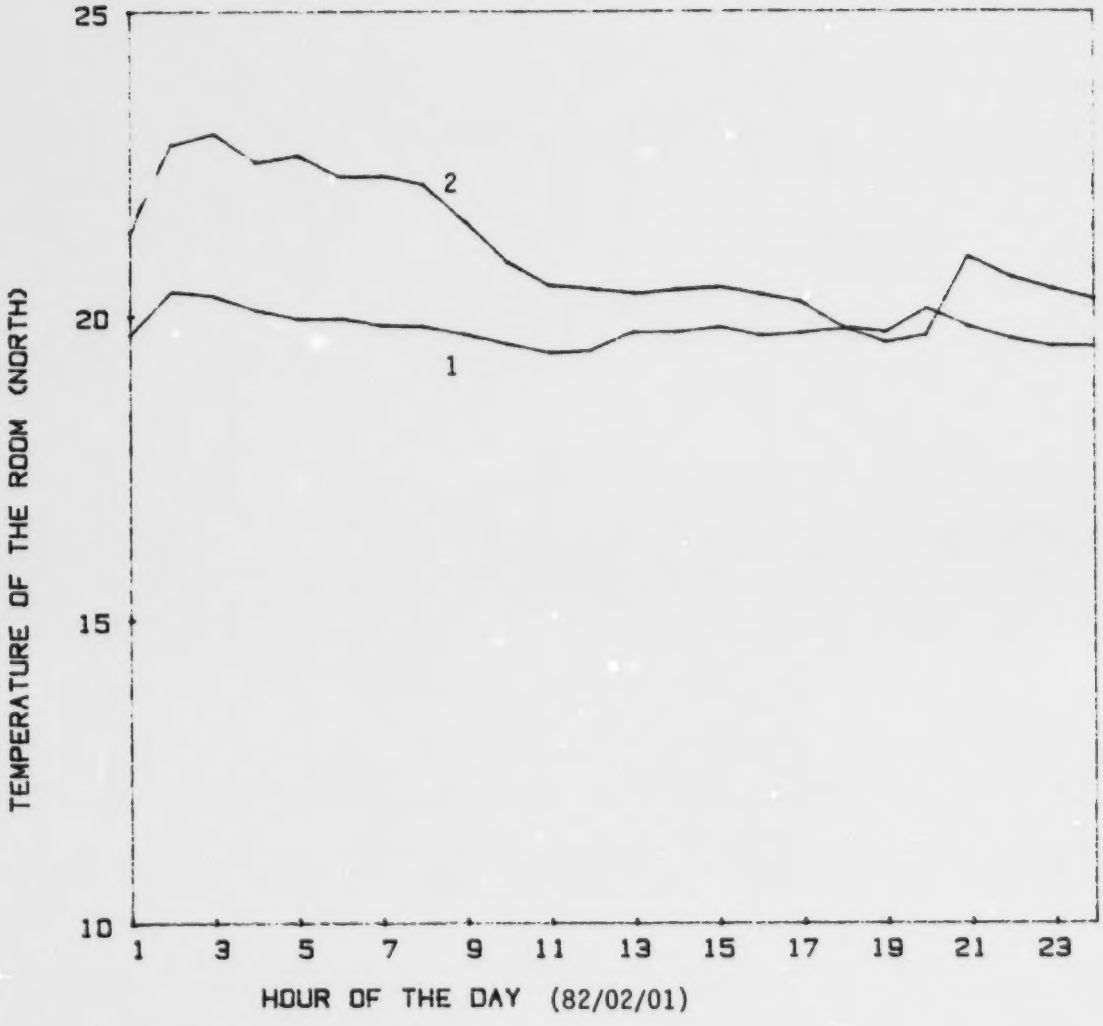


Figure 3.15 Hourly Values of Room Air Temperature - North Side

Table 3.5 Water Heating Loads and Solar Heating Contribution (in GJ)

December 1, 1981 to November 30, 1982

	DHW Projected	DHW Actual	Actual Solar to DHW	Adjusted Solar to DHW
D	5.92	16.86	8.46	8.46
J	6.25	17.28	6.09	6.09
F	5.80	16.24	1.53	-
M	6.42	-	0.	15.0
A	6.04	-	0.	-
M	5.91	-	0.	-
J	5.36	-	2.77	2.77
J	5.21	-	0.	0.
A	5.02	-	0.	0.
S	4.86	-	0.	0.
O	5.22	16.72	15.33	15.33
N	5.37	13.96	9.55	9.55
Total	67.4	194.5	43.7	57.2

The mains water temperature is shown in Figure 3.16. This temperature averages 10°C with a five degree swing depending on the season. The minimum mains water temperature occurs in February.

The domestic hot water system at Aylmer continuously circulates hot water through building piping. This method of operation ensures hot water at the taps, but is costly since heat must be supplied to overcome line losses. Figure 3.17 shows daily values of DHW energy consumption. The top line is the total energy required for the DHW system (solar and electric). The percentage of the total energy utilized (i.e. the amount of solar and electric heat that went to meeting the water load) is shown in Figure 3.18. The remainder is the energy lost due to auxiliary tank and line losses. Tank and line losses account for 28% (157 MJ/day) of the total energy supplied for DHW heating.

3.5.2 Solar DHW Heating

Solar heat delivery to the DHW load is summarized in Table 3.5. The adjusted solar heat delivery is an estimate of how much solar heat would have been supplied had the solar collectors been operational all year. The system can supply 57 GJ, 2 GJ more than anticipated at the design stage. Daily values of the solar contribution to the DHW system are shown in Figure 3.19.

When the temperature of the main solar storage tank is above the DHW setpoint temperature (i.e. November), the solar system can meet the hot water load (excluding tank and line losses). Because of solar system design, it is not possible for it to provide heat for tank and line losses. The solar contribution drops in direct proportion to the decrease in main storage tank temperature (see Figure 3.9 for tank temperature). It is important to note that even when the main storage tank temperature is too cold to provide space heating (below 30°C) it can supply 40% of the water heating load (excluding losses). Unfortunately problems with the system prevent energy being supplied to the DHW system when the solar space heating system is shut off. The potential for improved system performance by allowing solar heat to be delivered to the DHW system all year is discussed in Section 3.7.

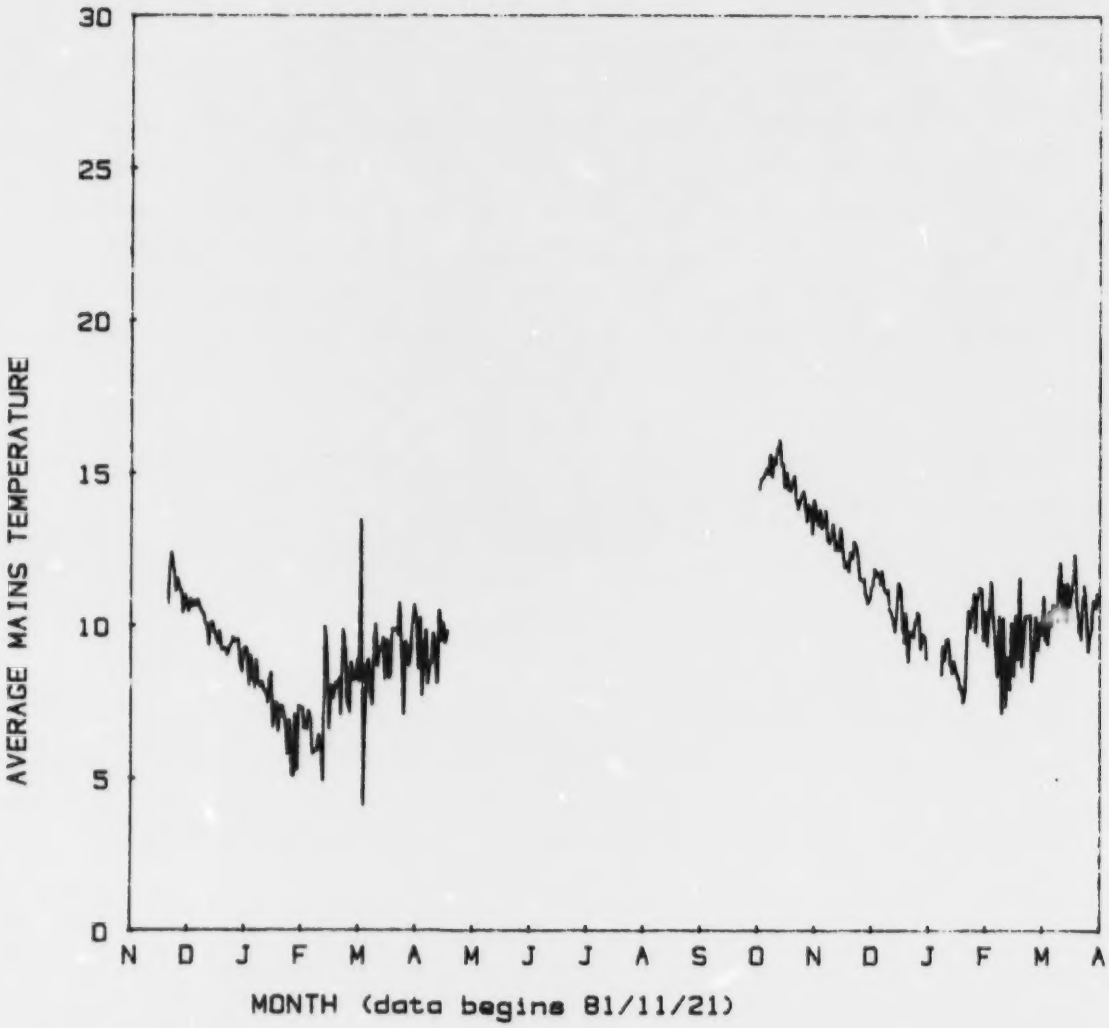


Figure 3.16 Daily Mains Water Temperature in Degrees Celsius

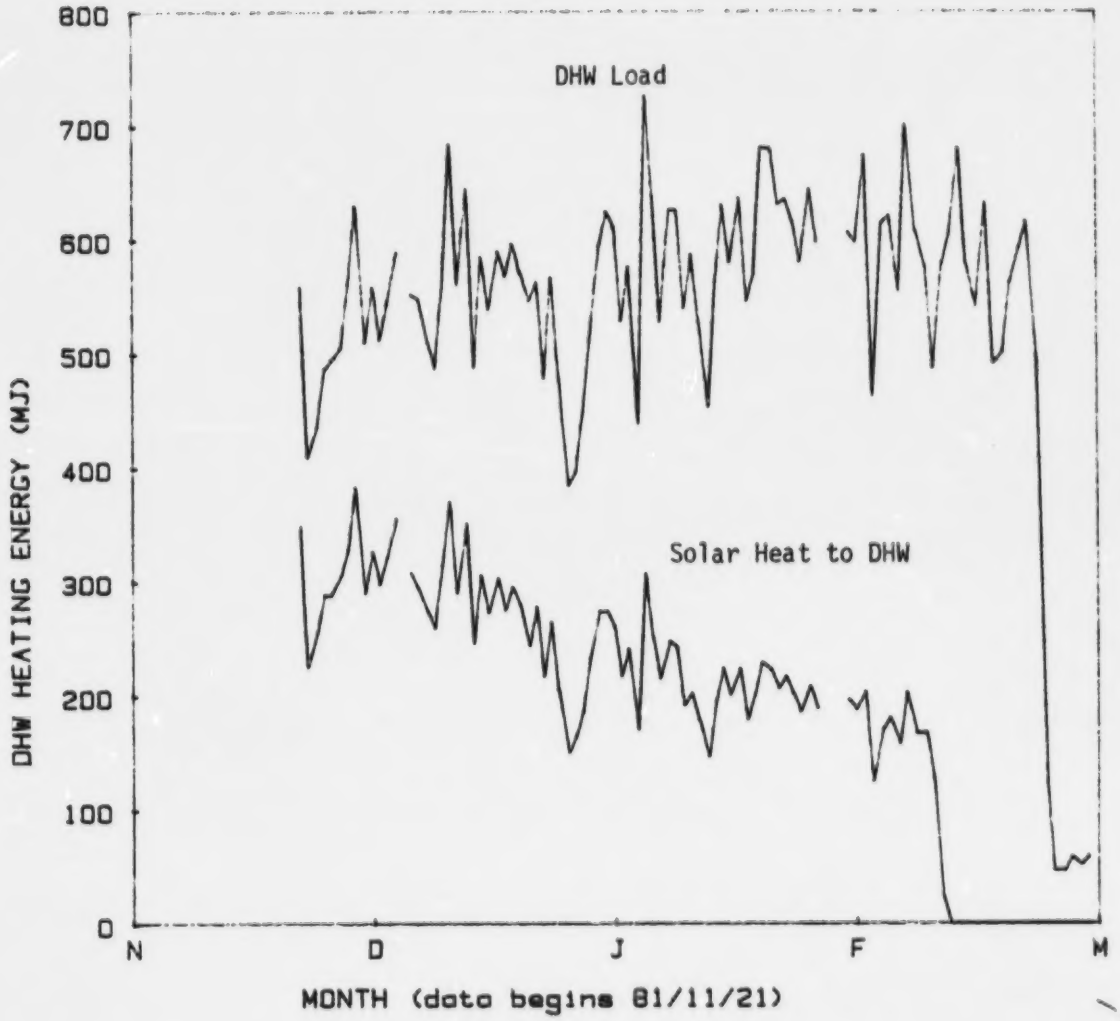


Figure 3.17 Daily Values of DHW Heating

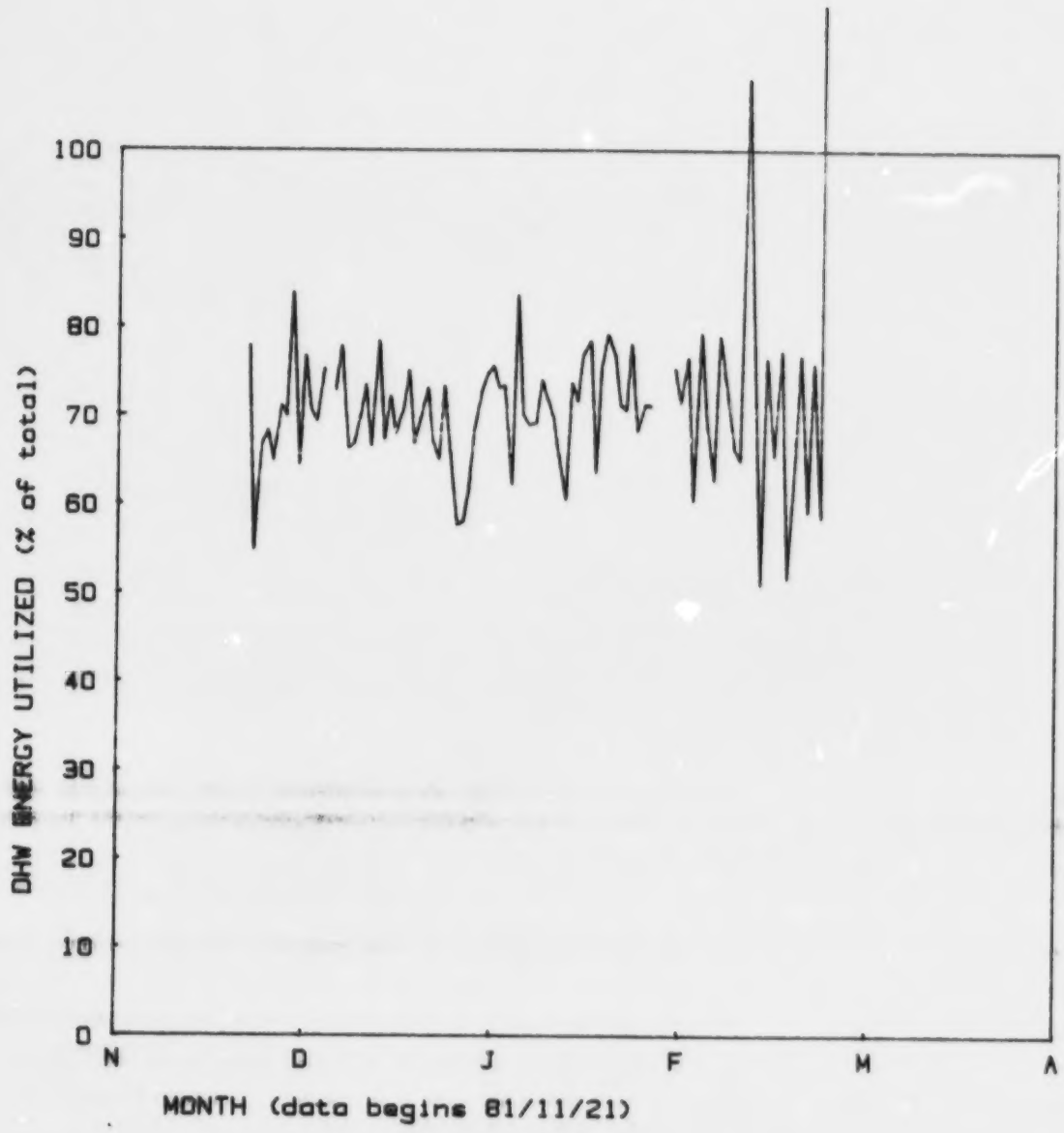


Figure 3.18 Daily Values of Percentage of DHW Heating Energy Utilized

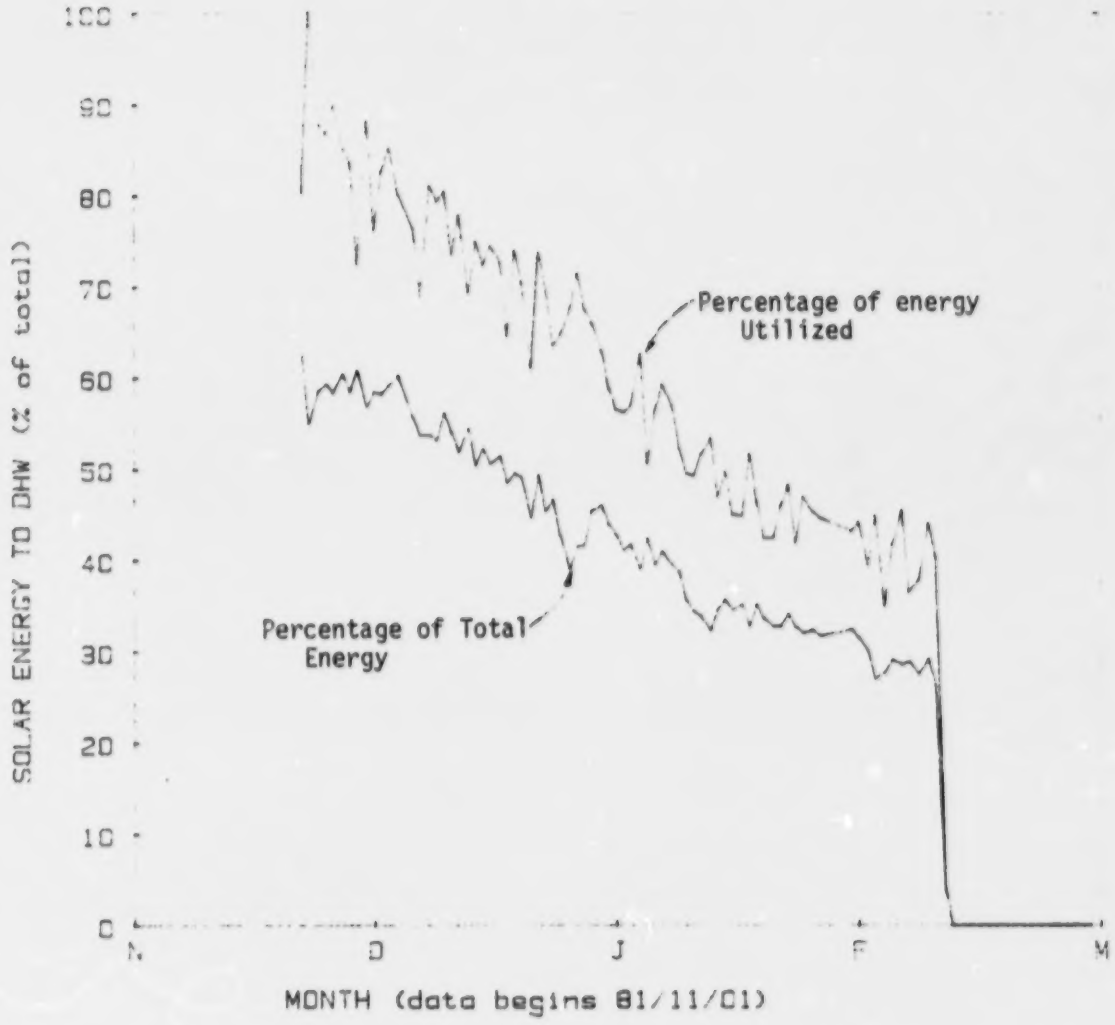


Figure 3.19 Daily Values of Percentage Solar Contribution to DHW Heating Load

The performance of the solar DHW system affects the space heating system. The larger than anticipated hot water load causes the energy in the main solar storage tank to become depleted sooner than anticipated. Thus, less solar energy is available for space heating.

3.6 The Ventilation System

The heating load due to ventilation is reduced by use of a heat wheel heat recovery unit. Monitoring problems limited the amount of suitable experimental data; nonetheless, the performance of the heat wheel is presented in Figure 3.20. Two lines are shown on this figure. The upper line is the effectiveness of the heat wheel which is based on minimum flow rate in either direction. The lower line is the efficiency of the heat recovery system which is based on the maximum flow rate in either direction.

The heat wheel has a fairly constant effectiveness of approximately 77%. This is close to the manufacturer's claimed efficiency of 80% (based on the system flow rates). The efficiency of heat recovery is approximately 62%, that is, 62% of the heat in the exhaust air is recovered.

The average air flow rates for the period December 1981 through February 1982 are 525 litres per second (supply) and 600 litres per second (exhaust). These values are considerably lower than the design values of 1380 litres per second (supply) and 1540 litres per second (exhaust). The low ventilation rate is probably the reason many of the occupants have been opening their windows.

The lower flow rates must either be a result of improper setting of flow rates after installation or a result of an increase in system pressure drop since installation. An examination of the heat wheel during a site visit in May 1984 showed a clogging of the air passages due to dirt and dust. The heat wheel has not been cleaned since installation. The ventilation air flow rates were examined for the January 1980 (the first winter of monitoring). The supply air flow rate was 700 litres per second and the exhaust air flow rate was 800 litres per second on average 33% higher than the values two years later. By January 1980 the heat wheel had been operating for one year. Thus, it would appear that the lower flow rates are due at least in part to a high pressure drop across the heat wheel.

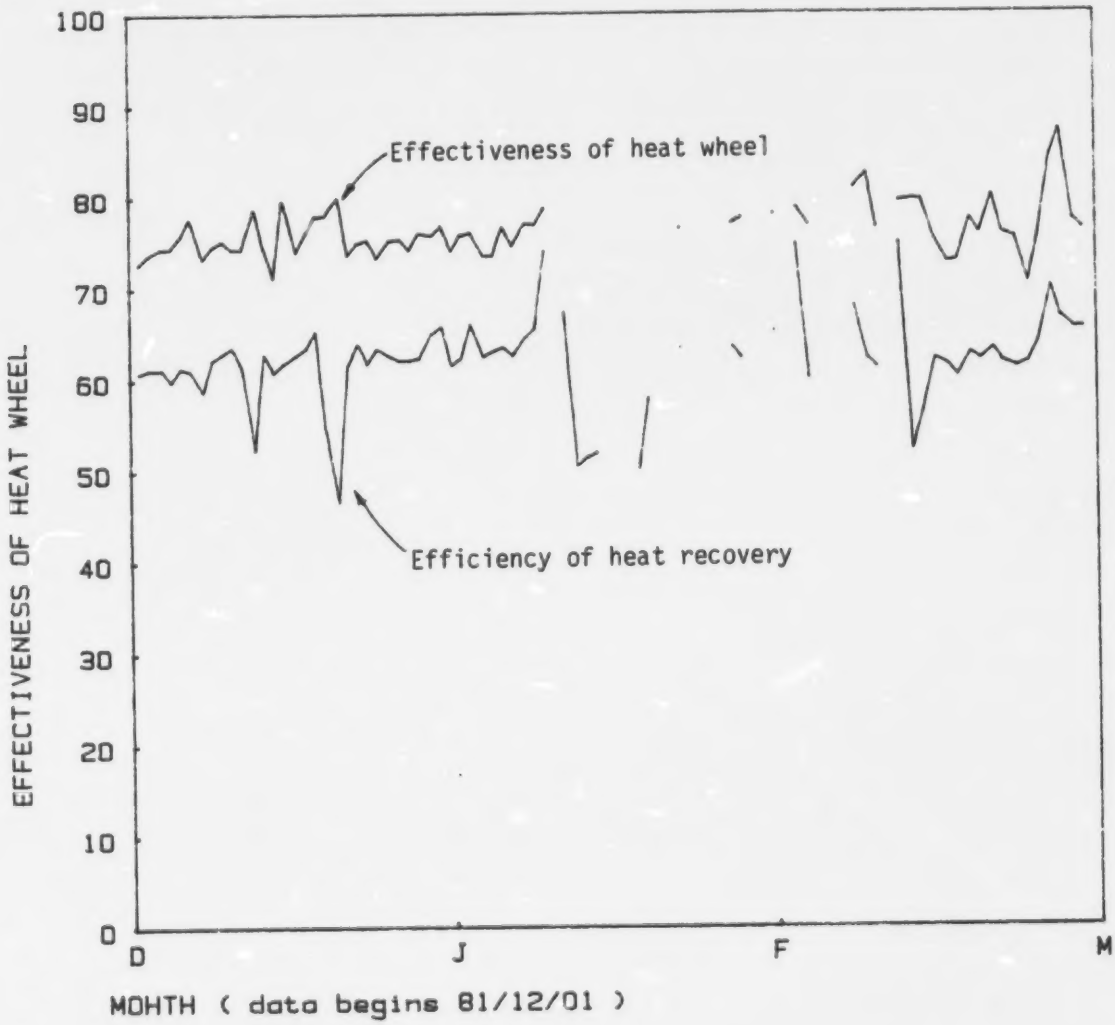


Figure 3.20 Daily Values of Ventilation Heat Recovery Performance

3.7 Potential Solar Heating System Performance

Sections 3.2, 3.4 and 3.6 describe the monitored performance of the solar heating system. In this section the potential for improved solar heating system through two modifications is discussed.

First, rather than daily cycling solar and electric heat to meet the space heating demand, the system could be operated to use solar heat for the first part of the winter and electric heat for the second part. If the solar heat is used more quickly the tank temperature will be lower. A lower tank temperature results in a lower collector inlet temperature and higher collector efficiencies. If, however, off-peak electrical rates are available, then the present mode of operation may result in lower building heating costs. Second, the system could be modified to allow for year-round heating of domestic hot water. This modification will result in lower tank temperatures (and therefore higher collector efficiencies) especially during the summer. The only way to determine the potential improvement of these modifications is by computer simulation.

The first step in this examination was to check the accuracy of the computer program in predicting existing solar heating system performance. The ENERPUB computer program was used to simulate the performance of the existing system one month at a time. For the simulation, monthly values of maximum load the solar heating system could supply given current operating conditions and initial storage tank temperatures were set equal to the actual values.

The simulated and monitored values of solar energy collected are presented in Table 3.6. This table shows that simulation can predict solar heating system performance within a few percent. No comparison could be made for January through March because the solar collection system was shut down. (The simulated values for January through March were used in Table 3.1 as the best estimate of existing system performance; shown in brackets).

Table 3.6 Accuracy of Computer Simulation

Month	Simulated Solar Energy Collected (GJ)	Actual Solar Energy Collected (GJ)
DEC	10.36	10.68
JAN	12.02	4.88 (12.02)*
FEB	26.66	0.0 (26.66)
MAR	31.96	0.0 (31.96)
APR	43.31	45.65
MAY	27.10	31.85
JUN	20.25	21.06
JUL	30.42	33.16
AUG	25.23	28.56
SEP	17.78	18.74
OCT	20.14	20.30
NOV	9.97	7.69
YEAR	275.2	288.01

* Bracketed values are a best estimate of energy collected had the system been operational.

Table 3.7 shows the simulated performance of the solar heating system if there is no daily cycling of solar and electric heat and if the system is modified to be able to supply DHW all year. The space and water heating loads are as given in Tables 3.2 and 3.5.

The simulation shows that the solar heating system can supply 264 GJ or 97% of the design value. The reason for this drastically improved performance is the lower tank temperature. The maximum temperature is 53°C instead of the monitored value of 71°C. This lower temperature results in higher collector efficiency and lower tank heat loss. Although solar heat cannot be delivered for space heating below 29°C, during the winter the tank temperature can drop below 29°C because heat can still be delivered to the domestic hot water load.

Table 3.7 Potential Solar Heating System Performance

	Solar Energy Collected (GJ)	Solar Energy Delivered to Space (GJ)	Solar Energy Delivered to DHW (GJ)	Average Tank Temperature (°C)
D	12.30	44.99	6.76	37.7
J	15.04	25.57	4.57	29.3
F	29.95	16.15	4.09	27.4
M	34.92	22.39	4.70	28.6
A	47.37	22.36	4.98	31.1
M	33.82	4.28	6.34	35.5
J	28.57	4.15	6.34	39.6
J	40.86	0.	7.44	44.9
A	33.24	0.	8.46	50.6
S	24.35	3.74	8.77	53.3
O	25.29	12.08	9.38	53.0
N	11.76	27.75	8.41	48.1
Total	337.5	183.46	80.24	

4. TOTAL BUILDING PERFORMANCE

Section 3 presented the performance of the six building systems. In this section the total building performance is summarized. The reasons for differences between design and monitored values are discussed in Section 3.

Table 4.1 summarizes the performance of the Aylmer Senior Citizens' Residence. The column labelled "design" is the performance expected by building designers (see Section 1.4). The "actual" column presents the performance for the period December 1, 1981 to November 30, 1982 (see Section 3). The "adjusted" values include the additional solar heat that would have been collected had the solar heating system not been shutdown for two-and-a-half months (see Sections 3.2 and 3.4). The "potential" column provides values for solar heating system performance if two improvements are made to system operation (see Section 3.7). The first improvement is to eliminate daily alternate use of solar and electric heat; the second improvement is to modify the system to allow for year round solar heating of domestic hot water.

One of the main differences between monitored and design performance is the high domestic hot water load and to a lesser extent high space heating load. The actual energy demand for hot water heating is almost three times that estimated by the designers. Demand for hot water averages 68 litres per person per day. This is not an excessive amount. It would appear that the hot water load was underestimated at the design stage. The space heating requirement was 22% higher than the design estimate. This is probably a result of open windows and a higher interior temperature than called for in the design. These higher loads result in a total building heating requirement (space and DHW) that is 60% higher than the design estimate.

The solar heating system was designed to supply almost all of the heating load (92%). This percentage can be misleading, especially if the heating load changes. Had the solar heating system supplied the amount of energy it was designed to, the percentage of the actual load met by solar would be only 58%. For a typical year the system supplies 47% of the heating load or 222 GJ. The 11% difference in performance is due to inefficient heat delivery (see Section 3.7) and lower collector

Table 4.1 Performance of Aylmer Senior Citizens' Residence in GJ per year

Building Floor Area = 1784 m^2
Collector Aperture Area = 184 m^2
Storage Volume = 900 m^3

	Design	Actual	Adjusted	Potential
Heating Load				
Space	227	278	278	278
Water	68	195	195	195
Total	295	473	473	473
Solar Heat				
Collected	384	223	291	338
Storage Losses	112	52	68	74
Delivered to Space	217	126	165	184
Delivered to DHW	55	44	57	80
Delivered Total	272	170	222	264
Auxiliary Heat				
to Space	10	152	113	94
to DHW	13	151	138	115
Total	23	303	251	209
Percent Solar	92	36	47	56

performance (see Section 3.2). Solar heating system performance is often quoted on the basis of GJ per square metre of collector area. This is because the amount of heat available from the sun is limited by the area for heat collection. The Aylmer solar heating system receives 5 GJ per year per square metre of collector. Of this 32% (1.58 GJ/m² annually) is collected and 24% (1.2 GJ/m² annually) is delivered to the load. Compared to other solar heating applications, these values are low. A good solar heating application (e.g. process water heating) would deliver over 40% (or 2 GJ/m² annually) of available solar radiation.

The performance of the system could be improved to 56% of the heating load (or 1.43 GJ/m²) if two changes are made to the system: eliminate daily alternate use of solar and electric heat (i.e. operate on solar heat until the main storage tank drops below 29°C) and modify system to allow for year round solar heating of domestic hot water (see Section 3.7).

Heat losses from the storage tank are only 61% of the design value. The main reasons for the lower heat loss are the lower tank temperature and possibly higher levels of insulation. Heat losses from the storage tank accounted for only 23% of the energy collected.

5. CONCLUSIONS

As a result of this study a number of conclusions can be made about the performance of Aylmer Senior Citizens' Residence.

1) Despite some early system problems, the solar heating system is operating reliably.
2) Building space heating consumption is 20% higher than expected because of higher indoor temperatures and higher air infiltration rates.
3) During a typical year the solar heating system collects 291 GJ of heat, 1.6 GJ per square metre of collector, 24% less than design. Possible reasons for this lower performance are lower collector thermal performance characteristics and inefficient control of solar heat delivery.
4) The solar storage tank heat loss is lower than expected because of higher insulation levels and sligthly lower than expected temperatures. Because of the location of the tank connections and the high collector flow rate, the tank shows very little temperature stratification.
5) For a typical year the solar heating system would supply 222 GJ of heat or 47% of total heating load. The system was expected to deliver 272 GJ or 92% of the load. The main reason for the low percentage contribution is the much higher than expected domestic hot water and space heating load.
6) The domestic hot water energy consumption is approximately three times greater than that projected. The main reasons for this discrepancy are higher hot water usage (68 litres/(person-day)) and a 70% efficient hot water delivery system.
7) Although the heat wheel heat recovery is operating efficiently, the ventilation system is not supplying the design air change rate. The reduced air flow rate is probably due to dirt build up in the heat wheel.
8) With improvements in solar heating system operation, solar heat could supply 264 GJ of heating, 97% of the design value.

6. REFERENCES

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3. Davis Engineering Limited. no date. Final Report on Monitoring Program at the Aylmer Senior Citizen's Apartment Building. Prepared for National Research Council, Solar Energy Project. Ottawa. Contract No. 01SX.31155-8-4435-2.

4. Davis Engineering Limited. 1982. Final Report, Aylmer Monitoring , November 1980-1982. Prepared for National Research Council, Solar Energy Project. Ottawa. DSS File No. 31155-8-4435-1.

5. Davis, Eryou and Associates Ltd. 1979. Installation, Management and Software Development for Monitoring of Solar Heating Systems at the Aylmer, Ontario Senior Citizen's Apartment. Prepared for National Research Council, Division of Building Research. Ottawa. Contract No. OSQ77-00130.

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9. Hooper, F.C., J.D. McClenahan and G.T. Williams. 1980. Solar Space Heating Systems Using Annual Heat Storage. Prepared for the U.S. Department of Energy, Solar Energy. Report No. DOE-CS-32939-12.

10. Hooper and Angus Associates Ltd. 1979. Aylmer Design Manual. Phase 1. Prepared for Ontario Ministry of Municipal Affairs and Housing. Toronto.

11. J.E. Hay. 1977. An Analysis of Solar Radiation Data for Selected Locations in Canada. Climatological Studies Number 32. Prepared for Fisheries and Environment Canada.

12. Frank Hooper, personal communication, September, 1984.

13. Sibbitt, B.E. Aylmer Solar System Performance Summary Tables (July, 1979 - March, 1983), August 1983, NRC Solar Energy Program.

Table 1 Monitoring Points for the Building Shell

Sensor	Measuring Quantity	Status
T15	fan coil return water temperature	operational
T22	fan coil supply water temperature	operational
T23	ambient air temperature	operational
T31	wall temperature, Unit #105	operational
T32	wall temperature, Unit #106	operational
T35	wall temperature, Unit #115	operational
T36	wall temperature, Unit #206	operational
T37	wall temperature, Unit #207	operational
T38	wall temperature, Unit #216	operational
F2	space heating loop water flow	operational
R2	insolation, horizontal surface	defective 79/09-80/05;82/03-04
R12	insolation, horizontal surface	removed 82/03
W17	total building electrical consumption	installed 81/03
WS	wind speed	defective 81/06-07;82/02; removed 82/03
WD	wind direction	defective 81/03;82/02; removed 82/03
AF1	fresh (supply) air flow	operational
AF2	building exhaust air flow	operational
T25	fresh (supply) air temperature	operational
T27	building exhaust air temperature	operational

Table 2 Monitoring Points for Solar Collection System

Sensor	Measuring Quantity	Status
T1	collector inlet water temperature	CPU malfunction 82/01; defective 83/01; CPU malfunction 82/01/10-15
T2	collector outlet water temperature	defective 80/01;82/04-12(T3 used)
T3	collector-tank return water temperature	CPU malfunction 82/01/10-15; defective 81/08-11;83/01
T4	collector supply pump inlet water temperature	operational but reads low
T5	collector pair 1 inlet water temperature	operational
T6	collector pair 1 outlet water temperature	operational
T7	collector pair 2 inlet water temperature	CPU malfunction 82/01/10-15
T8	collector pair 2 outlet water temperature	operational
T9	collector pair 3 inlet water temperature	CPU malfunction 82/01; defective 83/01-03
T10	collector pair 3 outlet water temperature	operational
T11	collector pair 4 inlet water temperature	CPU malfunction 82/01/10-15
T12	collector pair 4 outlet water temperature	
T23	ambient air temperature	operational
T102	collector supply pump outlet water temperature	operational
R1	insolation, array and middle	defective 81/06/01-05;82/06-11
R2	insolation, horizontal surface	defective 79/09-80/05;82/03-04
R3	insolation, inclined surface	defective 82/05-07
R4	insolation, array and bottom	defective 79/09-80/05;81/07-11; removed 81/11
R5	insolation, array and bottom	removed by 82/03
R6	insolation, array and middle	removed by 82/03
R7	insolation, array and top	removed by 82/03
R8	insolation, array top west	removed by 82/03
R9	insolation, array bottom west	removed by 82/03

Table 2 Monitoring Points for Solar Collection System (Continued)

Sensor	Measuring Quantity	Status
R10	insolation, array top east	removed by 82/03
R11	insolation, array bottom east	removed by 82/03
R12	insolation, horizontal surface	removed by 82/03
F1	collector loop water flow	Steady-state value shifts: 81/01,82/04
W3	electrical consumption, P3	Error:=0 when collectors on and steady, replaced 82/11/10
W4	electrical consumption, P4	Error:=0 when collectors on and steady

Table 3 Monitoring Points for Solar Storage Tank

Sensor	Measuring Quantity	Status
T47	tank and bottom water temperature	defective 79/11-80/01;81/12-83/03
T48	tank and bottom water temperature	defective 81/12-82/11
T49	tank and bottom water temperature	defective 81/12-82/11
T50	tank and (below midline) water temperature	defective 81/12-83/03
T51	tank and (above midline) water temperature	questionable 81/12-82/11
T52	tank and (above midline) water temperature	calibration exercise 82/06
T53	tank and (above midline) water temperature	questionable 81/12-82/11
T54	tank and top water temperature	questionable 81/12-82/11
T55	tank cover insulation temperature	defective 82/01
T56	tank cover insulation temperature	CPU malfunction 82/01; defective 83/01
T57	tank cover insulation temperature	CPU malfunction 82/01; defective 83/01
T58	tank top surface temperature	CPU malfunction 82/01
T59	tank top surface temperature	CPU malfunction 82/01
T60	tank top surface temperature	CPU malfunction 82/01; defective 83/01-02
T104	tank edge, bottom, water temperature	questionable 81/12-83/03
T105	tank edge, bottom, water temperature	defective 79/10; questionable 81/12-83/03
T106	tank edge (below midline) water temperature	calibration exercise 82/06
T107	tank edge (above midline) water temperature	defective 81/03; questionable 81/12-82/03
T108	tank edge (above midline) water temperature	questionable 81/12-82/03
T109	tank edge, top, water temperature	defective 81/12

Table 4 Monitoring Points for Heat Delivery System

Sensor	Measuring Quantity	Status
T13	tank inlet water temperature	defective 80/04;82/11
T14	tank outlet water temperature	defective 82/06-83/03 80/01
T15	fan coil outlet water temperature	defective 83/03
T16	heating circulation pump inlet water temperature	reads low 79/12;81/12
T22	boiler outlet water temperature	operational
T39	air temperature, Unit #105	operational
T40	air temperature, Unit #106	operational
T43	air temperature, Unit #115	operational
T44	air temperature, Unit #206	operational
T45	air temperature, Unit #207	operational
T46	air temperature, Unit #216	operational
T101	heating circulation pump outlet water temperature	operational
F2	space heating loop water flow	operational
W1	electrical consumption, P1	operational
W2	electrical consumption, P2	operational
W8	electrical consumption, auxiliary boiler	operational
W11	electrical consumption, Unit #105	operational
W12	electrical consumption, Unit #106	defective 83/02-03
W13	electrical consumption, Unit #115	operational
W14	electrical consumption, Unit #206	operational
W15	electrical consumption, Unit #207	operational
W16	electrical consumption, Unit #216	operational
W17	building total electrical consumption	installed 81/03: operational

Table 5 Monitoring Points for the Domestic Hot Water System (DHW)

Sensor	Measuring Quantity	Status
T17	DHW heat exchanger inlet water temperature	defective 82/10;82/11/01-04
T18	DHW heat exchanger outlet water temperature	defective 82/09-10;82/11/01-04
T19	preheat tank inlet water temperature	CPU malfunction 82/01; defective 83/01
T20	preheat tank outlet water temperature	operational
T21	electrical DHW tank outlet water temperature	operational
T100	city water mains water temperature	operational
T103	DHW recirculator return water temperature	defective 82/11
F3	DHW heat exchanger loop water flow	operational
F4	water flow, city water mains to building	operational
F5	DHW supply loop water flow	defective 80/03-04
W5	electrical consumption, P5	operational
W6	electrical consumption, P6	defective 79/07-11
W10	DHW heater electrical consumption	defective 82/02-11

Table 6 Monitoring Points for Ventilation System

Sensor	Measuring Quantity	Status
T23	ambient air temperature	operational
T25	building supply air temperature upstream of heat wheel	defective 83/01
T26	(supply air) fan coil outlet air temperature	operational
T27	building exhaust air temperature downstream of heat wheel	defective 80/03
T28	exhaust air temperature upstream of heat wheel	operational
T69	fan coil inlet water temperature	defective 82/12-83/01
T70	fan coil outlet water temperature	operational
T71	supply air temperature downstream of heat wheel	operational
F6	supply air fan coil loop water flow	operational
AF1	building exhaust air flow	operational
AF2	building supply air flow	defective
W7	exhaust fan electrical consumption	operational
W9	supply air fan electrical consumption	defective 82/11-83/03
P1	pressure difference across heat wheel (supply air)	defective 80/02
P2	pressure difference across heat wheel (exhaust)	defective 80/02;81/10;82/11;83/01
P3	pressure in tubes (supply air)	operational
RH1	exhaust air relative humidity upstream of heat wheel	defective 81/03
RH2	building supply air relative humidity upstream of heat wheel	defective 81/03;81/10;82/11
RH3	building exhaust air relative humidity downstream of heat wheel	defective 81/03

APPENDIX B

Analysis of Suitability of Monitored Data

The monitoring contractor produced daily summaries of building performance for the period July 1979 to March 1983. Although these summaries contain considerable information, errors in the analysis software and failure of several sensors reduce their usefulness. The National Research Council of Canada (NRC) has taken the "raw" data and processed it to remove as many errors as possible and provide interpolated data when the monitoring system went down for periods of less than one hour. This "clean" data was then used to produce daily summaries of the more important parameters, specifically those dealing with the solar heating system.

The NRC daily summaries[13] were examined for suitability of monitored information for each of the six building systems under study: building shell, solar collector system, solar storage tank, space heating system, DHW heating system, and ventilation system. The results of this initial examination are summarized in Figures B.1 - B.6. If, during a given interval, a particular system was activated and the relevant data appears to be consistent, then that interval is considered to merit further investigation. Data for a given month is denoted "complete" if there appears to be valid data for more than twenty 24-hour periods during the month, and "partial" if there are fewer than twenty but more than ten days of pertinent and reasonably consistent data available.

The selection of an interval of evaluation for each building component is outlined below.

B.1 The Building Shell

It was felt that no purpose would be served in examining building shell heat losses during the summer, when the space heating system was not operating and building heat loss was negligible or negative (i.e., heat gains).

The building was monitored over four winters. There appears to have been a number of malfunctions connected with the monitored system in the 1980-81 winter (see Figure B.1), thus this period cannot be used to evaluate the building shell. The winter of 1979-80 could be analysed. During this period, however, the total building electricity consumption was not measured. This quantity is needed to estimate heat delivered to load and internal gains due to lights etc. It is felt that sufficient data exist for the winter months of 1981-82 and 1982-83 to enable a reasonably accurate assessment of building heat losses. The proposed evaluation period is illustrated in Figure B.1.

B.2 Solar Collection System

The operation of the solar collection system was difficult to assess during 1979, 1980 and 1981 because of the problems encountered with storage tank leakages and monitoring system hardware failure. This interval seems to have been plagued with malfunctions in the disk drive and integrated circuitry of the data acquisition system computer, and in several of the pyranometers (R1, R3). The best period for determining the performance of the solar collection system is the interval from March to November of 1982 (see Figure B.2). It is important to note that a correction factor will have to be included in the first five months of this period, since four of the collector panels had been shut down due to leakage.

B.3 Solar Storage Tank

The storage tank and related monitoring sensors have been plagued with a series of malfunctions and failures. The performance of the tank cannot be examined when it was leaking or drained (July 1979 to May 1981). The monitoring system experienced problems for most of 1981 (see Figure B.3). During the period from December 1981 to October 1982 the output of all but two of the tank temperature sensors drifted to varying degrees. The two sensors which were operating (T52 and T106) do not provide adequate information to determine temperature stratification and to a lesser extent heat losses in the storage tank. Thus, the only time period which accurately reflects the performance of the tank is the interval from November 1982 to March 1983, inclusive (see Figure B.3).

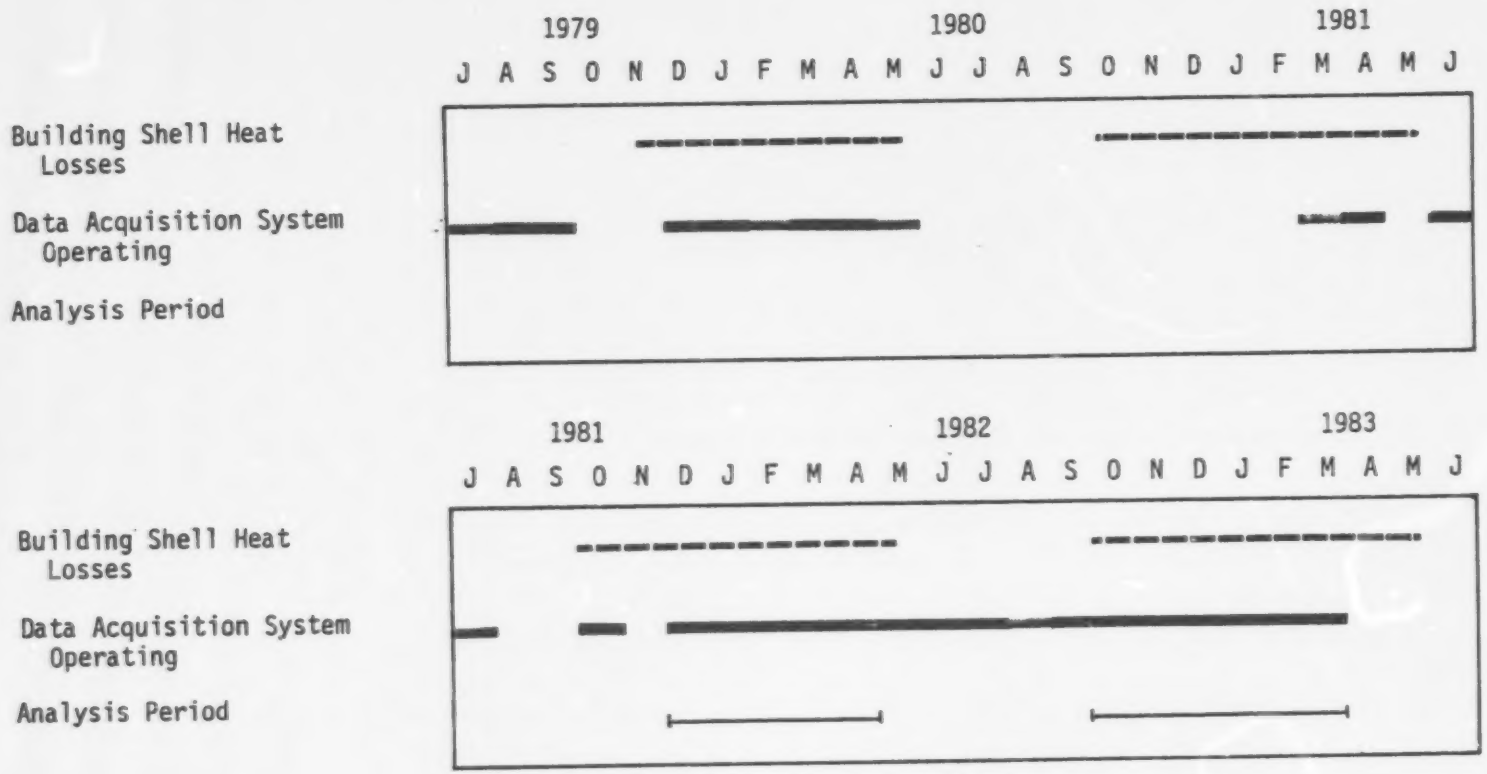
1979
1980
1981
J A S O N D J F M A M J J A S O N D J F M A M J
Building Shell Heat Losses
Data Acquisition System Operating
Analysis Period
1981
1982
1983
J A S O N D J F M A M J J A S O N D J F M A M J
Building Shell Heat Losses
Data Acquisition System Operating
Analysis Period
Legend:
System fully functional/activated
Complete data available
Partial data available
Suggested interval of system analysis

Figure B.1 Performance Analysis Period for Building Shell Heat Losses

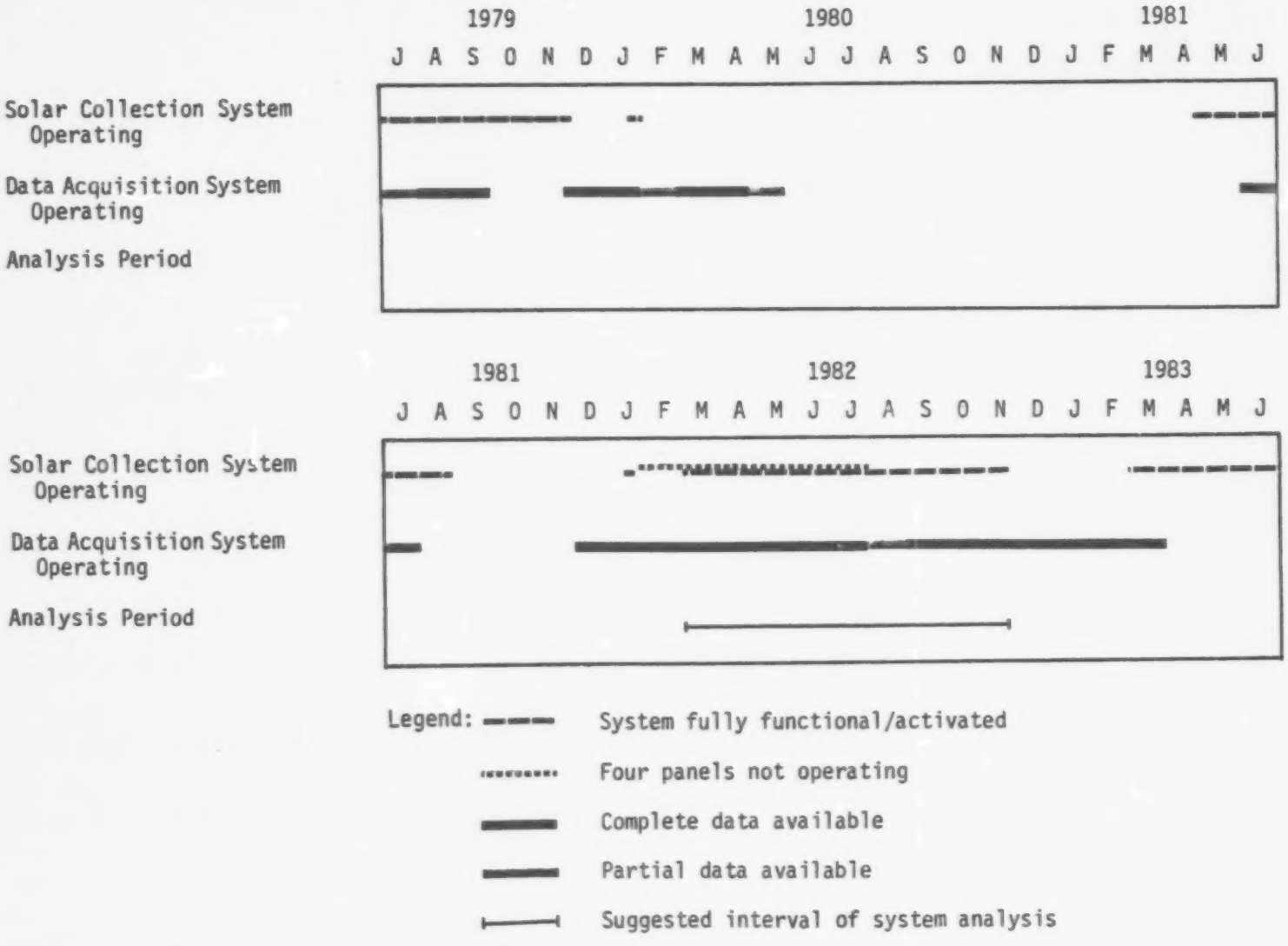
1979
1980
1981
J A S O N D J F M A M J J A S O N D J F M A M J
Solar Collection System Operating
Data Acquisition System Operating
Analysis Period
1981
1982
1983
J A S O N D J F M A M J J A S O N D J F M A M J
Solar Collection System Operating
Data Acquisition System Operating
Analysis Period
Legend:
System fully functional/activated
Four panels not operating
Complete data available
Partial data available
Suggested interval of system analysis

Figure B.2 Performance Analysis Period for Solar Collection System

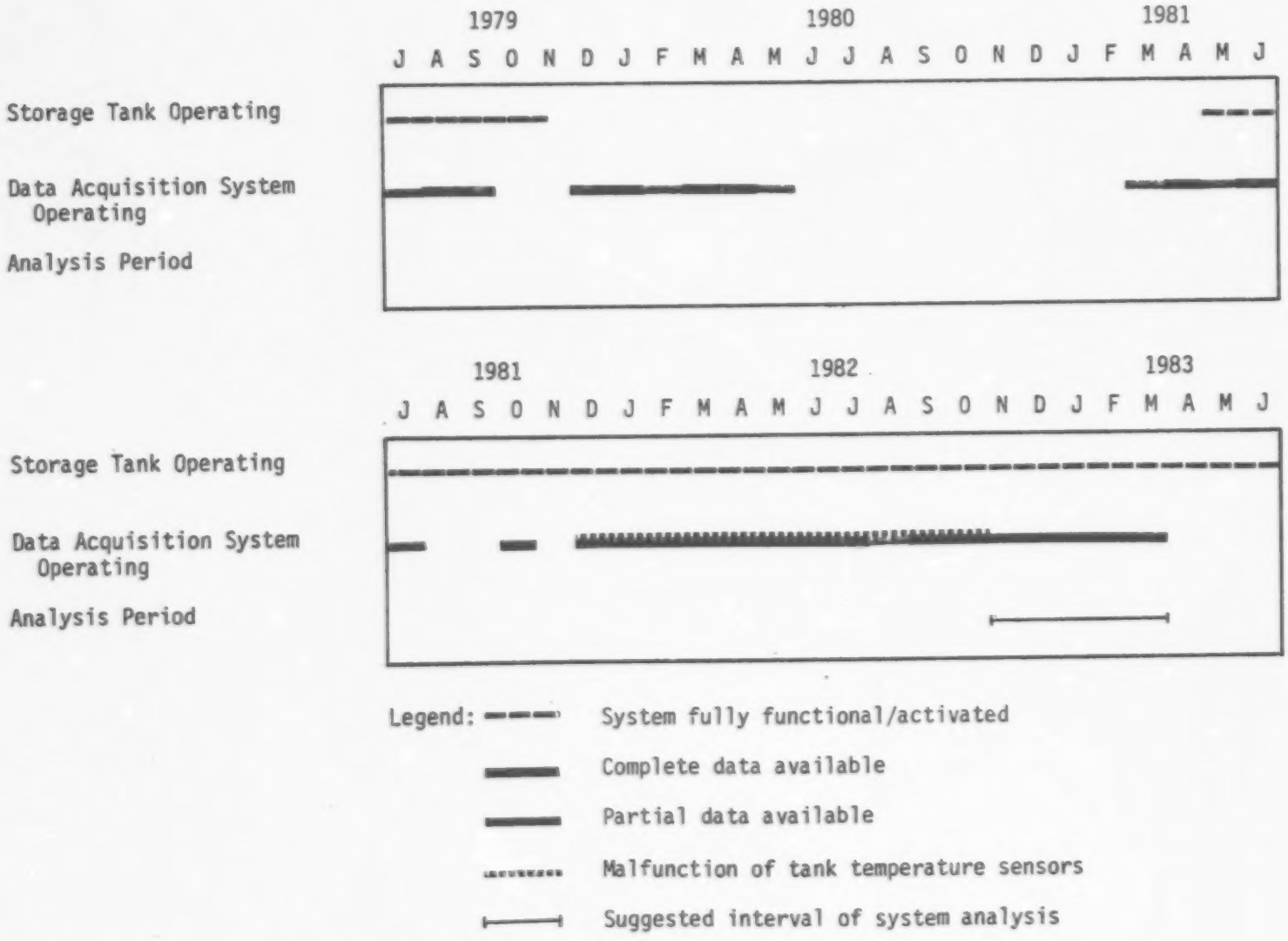
1979
1980
1981
J A S O N D J F M A M J J A S O N D J F M A M J
Storage Tank Operating
Data Acquisition System Operating
Analysis Period
1981
1982
1983
J A S O N D J F M A M J J A S O N D J F M A M J
Storage Tank Operating
Data Acquisition System Operating
Analysis Period
Legend:
System fully functional/activated
Complete data available
Partial data available
Malfunction of tank temperature sensors
Suggested interval of system analysis

Figure B.3 Performance Analysis Period for Storage Tank

B.4 Heating System

The building heating system was not fully operational as designed until October of 1981, a result of the combination of storage tank leakage and early problems with the three-way valve. The space heating monitoring system operated erratically in November 1981 and so the system cannot really be properly investigated until December 1981. The space heating system operating as all electric could be examined for parts of the 1979-80 winter. It is felt, however, that the intervals from December 1981 to April 1982 and from October 1982 to March 1983 provide a sufficient time period to evaluate the performance of the space heating system in solar and electric operating modes.

B.5 The Domestic Hot Water System

As seen in Figure B.5, there is little or no data regarding the DHW system until December 1981. Problems included leakage of the solar storage tank, malfunction of the electrical consumption monitor on Pump 6 and intermittent computer breakdowns caused by overheating. Also during this period the plumbing had been manually adjusted so that recirculated hot water returned to the preheat tank instead of the auxiliary tank in order to provide extra hot water capacity. This adjustment, however, results in increased heat losses and makes it difficult to analyse the performance of the system. The period from December 1981 to May 1982 appears to be satisfactory for analytical purposes, and should provide some contrast between solar/auxiliary and auxiliary/only operational modes. The remainder of the monitored data is characterized by the occasional malfunction of thermistors T17 and T18 which determine the contribution of solar energy to the DHW system.

B.6 The Ventilation System

The exhaust heat recovery system was typically employed only during the winter months (November - March; see Figure B.6). Monitored data are incomplete or invalid until late November 1981. Most of

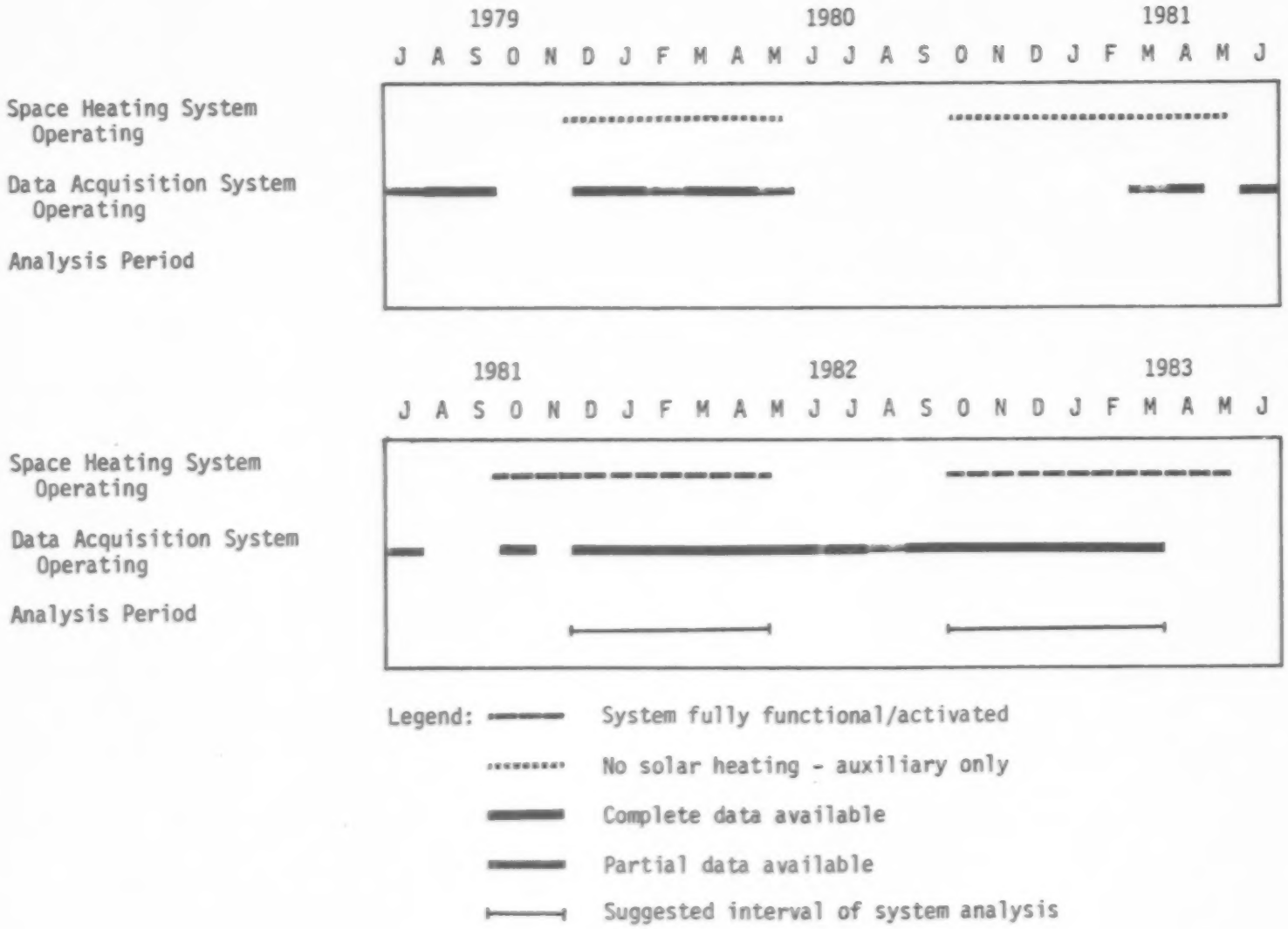
1979
1980
1981
J A S O N D J F M A M J J A S O N D J F M A M J
Space Heating System Operating
Data Acquisition System Operating
Analysis Period
1981
1982
1983
J A S O N D J F M A M J J A S O N D J F M A M J
Space Heating System Operating
Data Acquisition System Operating
Analysis Period
Legend:
System fully functional/activated
No solar heating - auxiliary only
Complete data available
Partial data available
Suggested interval of system analysis

Figure B.4 Performance Analysis Period for Space Heating System

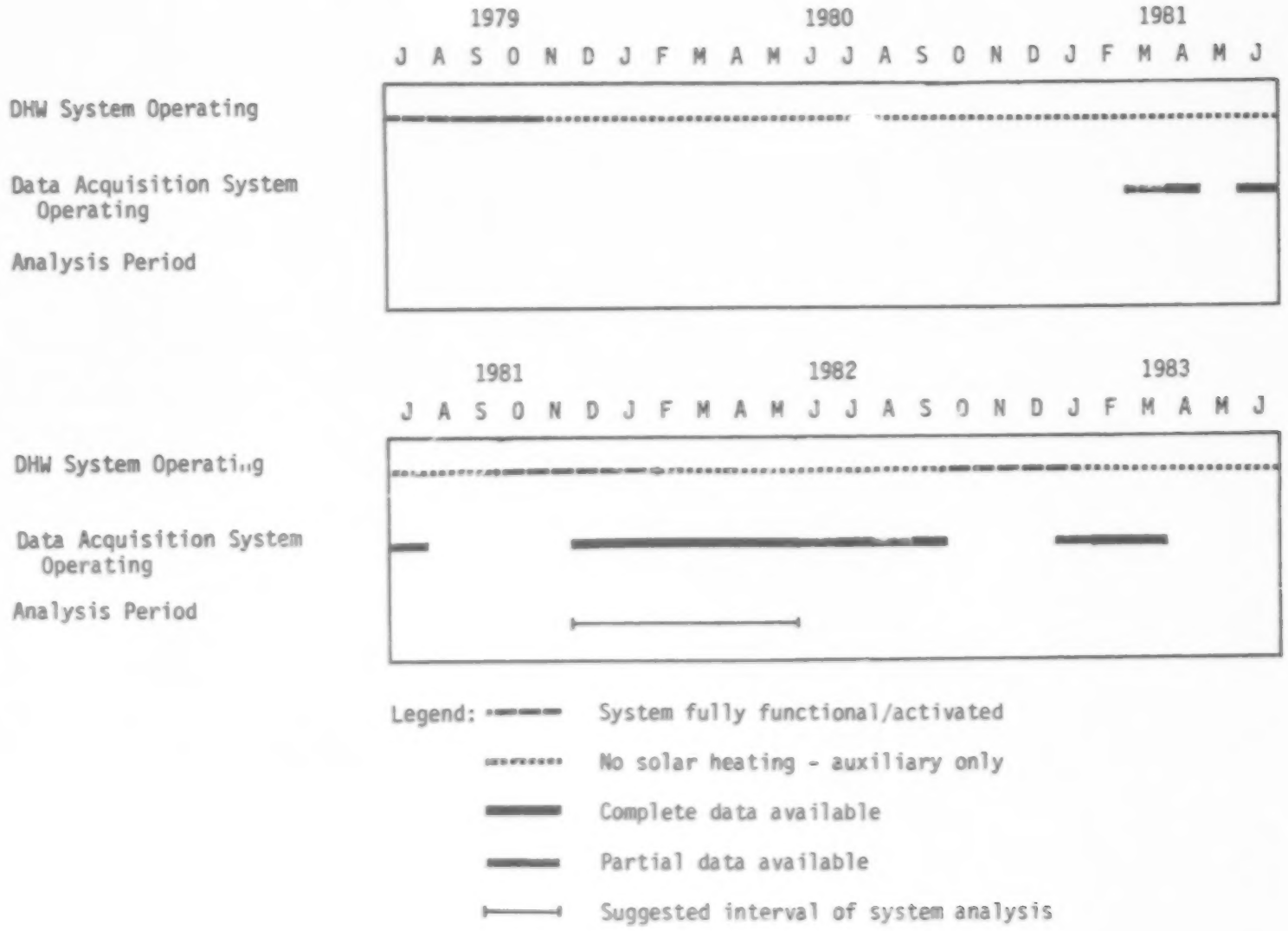
1979
1980
1981
J A S O N D J F M A M J J A S O N D J F M A M J
DHW System Operating
Data Acquisition System Operating
Analysis Period
1981
1982
1983
J A S O N D J F M A M J J A S O N D J F M A M J
DHW System Operating
Data Acquisition System Operating
Analysis Period
Legend:
System fully functional/activated
No solar heating - auxiliary only
Complete data available
Partial data available
Suggested interval of system analysis

Figure B.5 Performance Analysis Period for DHW System

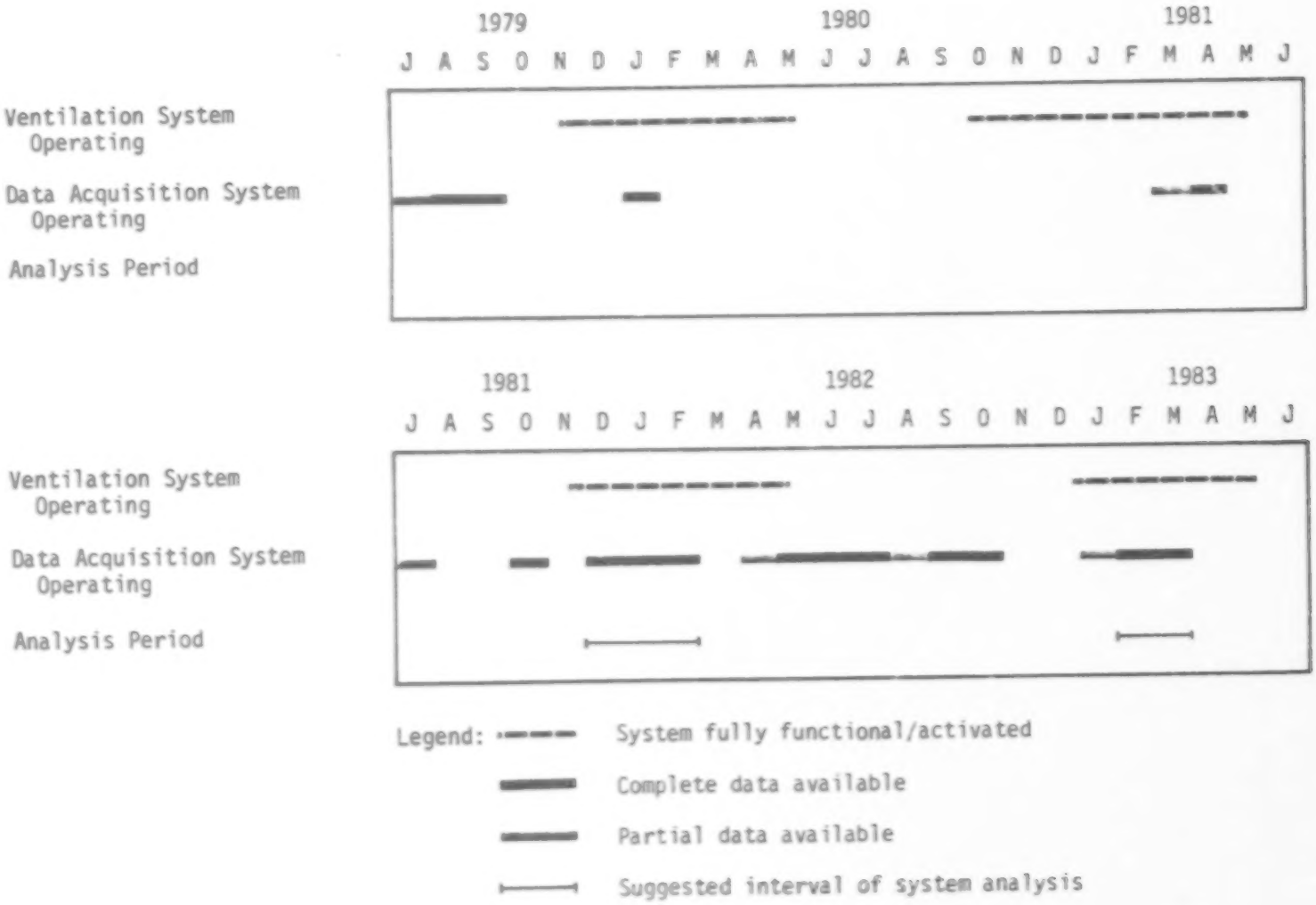
1979
1980
1981
J A S O N D J F M A M J J A S O N D J F M A M J
Ventilation System Operating
Data Acquisition System Operating
Analysis Period
1981
1982
1983
J A S O N D J F M A M J J A S O N D J F M A M J
Ventilation System Operating
Data Acquisition System Operating
Analysis Period
Legend:
System fully functional/activated
Complete data available
Partial data available
Suggested interval of system analysis

Figure B.6 Performance Analysis Period for Ventilation System

the problems in monitoring this system appear to involve the thermistor in the fresh-air fan coil unit (T69) and the sensors monitoring the air flow and relative humidity of the intake air (AF1 and RH2, respectively). It would seem that the only valid intervals for examining the operation of the ventilation/heat recovery system are December 1981 to February 1982, and February and March of 1983.

APPENDIX C

Data Analysis Technique

In this appendix the formulae used to calculate the performance fo the six building systems from the monitoring system sensor are presented. Figures 1.4 to 1.7 show the location of the sensors and Appendix A gives the definitions of the sensors.

Building Shell

Internal gains = QE + (QS_{dhw} - QT_{dhw}) - QB - QPF - AC - SP - P10

QPF = Energy of pumps and fans (MJ)
(W1 = W2 + W3 + W4 + W5 + W6 + W7 + W9) X 0.0036

QE = Building total electrical (MJ)
a) 1979 - 1980 Data
QPF + [((W11 + W12 + W13 + W14 + W15 + W16) X 29/6) X 0.0036]
b) 1981 - 1983 Data
QPF + (W17 X 0.0036)

QS_{dhw} = Solar energy to DHW (MJ)
Daily Sum of F3 X ρ X Cp X (T17 - T18)

QT_{dhw} = Total energy to DHW (MJ)
Daily sum of (W5 + W6 + W10 + DHW portion of (W3 + W4) X 0.0036)

QB = Energy of boiler (MJ)
Daily sum of W8 X 0.0036

AC = Energy used to cool monitoring room (MJ)
a) before 82/03/10 AC = 0.0
b) after 82/03/10 AC = 200.0

SP = Pumps for solar collectors
Collected energy X 0.1
= [Daily sum of F1 X ρ X Cp X (T2 - T1)] X 0.1
Note: After 82/03/30 T3 was substituted for T2

P10 = A retrofit pump with no wattmeter
a) between 82/02/09 and 82/09/30 P10 = 311.0 MJ
b) after 83/01/20 P10 = 311.0 MJ
c) All other times P10 = 0.0

Solar gains = Incident Energy X Correction Factor

Incident Energy (MJ)

= Daily sum of R1 X Collector Area X Elapsed Time

Correction Factor

corrects for shading and sun position

Building Heat Loss Coefficient (UA_b) = Q_{out} /(T_i - T23)

Q_{out} = QT_{space} + Internal gains + Solar gains (MJ)

QT_{space} = Total energy to space (MJ)

= Daily sum of (W1 + W2 + W8 + Space portion of (W3 + W4)) X 0.0036

T_i = Corrected average interior wall temperature (C)

= [(T31 + T32 + T35 + T36 + T37 + T38)/6] + 6

T23 = Ambient temperature

Solar Collection System

Solar collected = Collected solar energy (MJ)

= Daily sum of F1 X ρXCp X (T2 - T1)

Note: T3 was substituted for T2 after 82/03/30

Temperature rise across collectors (°C)

Pair 1: T5 - T6

Pair 2: T7 - T8

Pair 3: T9 - T10

Pair 4: T11 - T12

Collector Efficiency (%)

[Solar Collected / (maximum of R1, R2)] X 100

-expressed as a percentage

Reflector performance = R1/R3

Storage Tank

Average Storage Tank Temperature (C)

- time weighted average over the day with the following sensors

a) 1978 - 1980 Data

T48, T49, T52, T53, T106, T108, T109

b) 81/03 - 82/11/09 Data

T52, T106

c) 82/11/09 - 83/03 Data

T53, T106, T10[illegible]108, T109

Tank heat loss = solar collected - total energy used - net energy stored (MJ)

Solar collected (MJ) - see above

Total energy used (MJ)

QT_{space} (when positive) + QS_{dhw} (when positive)

QT_{space} - see above

QS_{dhw} - see above

Net energy stored (MJ) = daily sum of changes in storage tank temperature X 3546

For Data see average storage tank temperature above

Heat Delivery System

Solar to Space (MJ = F2 X ρ X Cp X (T101 - T15)

Domestic Hot Water System

Solar to DHW (MJ) = Daily sum of F3 X ρ X Cp X (T17 - T18)

DHW Energy Utilized

a) Data before 81/11/19 or After 82/02/11

= Daily sum of F4 X ρ X Cp X (T21 - T100)X (T21 - T100)

b) Data between 81/11/19 and 82/02/11

= Daily sum of (F4 - F5) X ρ X Cp X (T21 - T100)X (T21 - T100)

Ventilation System

Effectiveness of heat wheel (%)

$$[AF1 \times \rho \times Cp \times (T28 - T27)] / [(\text{minimum of } AF1, AF2) \times \rho \times Cp \times (T28 - T25)] \times 100$$

expressed as a percentage

Efficiency of heat recovery (%)

$$[AF1 \times \rho \times Cp \times (T28 - T27)] / [(\text{maximum of } AF1, AF2) \times \rho \times Cp \times (T28 - T25)] \times 100$$

expressed as a percentage

APPENDIX D

Performance of Aylmer Senior Citizens' Residence - As Designed

SOLAR HEATING SYSTEM: -NO HEAT PUMP

C. COLLECTOR DATA

C1	NUMBER OF COLLECTORS	112.00
C2	COLLECTOR SLOPE (DEGREES)	60.00
C3	COLLECTOR ORIENTATION (SOUTH=0,EAST=+, DEG.)	.00
C4	FLUID : 1-WATER, 2-PROP GLYCOL, 3-ETHY GLYCOL	1.00
C5	PERCENTAGE OF FLUID THAT IS GLYCOL (%)	.00
C6	GROSS AREA OF ONE COLLECTOR (M2)	2.05
C7	FR-TAU-ALPHA (TEST)	.81
C8	FR-UL (W/(M2*C)) (TEST)	5.27
C9	COLLECTOR TEST FLOW RATE (L/MIN) (PER COLLECTOR)	3.05
C10	COLL. TEST FLUID 1-WATER,2-PROP GLY,3-ETHY GLY	1.00
C11	PERCENTAGE OF TEST FLUID THAT IS GLYCOL (%)	.00
C12	INCIDENT ANGLE MODIFIER	

I	1	2	3	4	5
THETA	15.000	30.000	45.000	60.000	75.000
AKT	1.000	1.000	.930	.800	.700

T. TRANSFER DATA

T1	COLLECTOR-STORAGE HX EFFECTIVENESS	1.00
T2	REQUIRED COLL-STORAGE TEMP. DIFFERENCE (C)	1.70
T3	POWER OF PUMPS 1&2 (W)	2200.00
T4	COLLECTOR LOOP FLOW RATE (L/MIN)	342.00

S. SOLAR STORAGE TANK

S1	VOLUME OF SOLAR STORAGE TANK (LITRES)	********
S2	ORIENTATION: 1 - HORIZONTAL, 2 - VERTICAL	2.00
S3	DIAMETER OF SOLAR STORAGE TANK (M)	6.70
S4	RSI VALUE OF TANK INSULATION (M2-C/W)	6.00
S5	SURROUNDING TEMPERATURE (-100 FOR OUTDOORS)	10.00
S6	LOCATION OF COLLECTOR RETURN CONNECTION	.00
S7	LOCATION OF COLLECTOR SUPPLY CONNECTION	1.00
S8	LOCATION OF MAINS WATER INLET CONNECTION	1.00
S9	LOCATION OF MAINS WATER OUTLET CONNECTION	.00
S10	MAXIMUM STORAGE TANK TEMPERATURE (C)	79.00
S11	MINIMUM ALLOWABLE STORAGE TEMP.(C)	4.00
S12	STARTING TEMPERATURE (C)	42.00

P. COLLECTOR AND BUILDING PIPE DATA

P1	LENGTH OF COLLECTOR SUPPLY PIPE (M)	20.00
P2	SURROUNDING TEMP. COLLECTOR SUPPLY PIPE (C)	20.00
P3	COLLECTOR SUPPLY PIPE INSIDE DIAMETER (MM)	60.00
P4	LENGTH OF COLLECTOR RETURN PIPE (M)	20.00
P5	SURROUNDING TEMP. COLLECTOR RETURN PIPE (C)	20.00
P6	COLLECTOR RETURN PIPE INSIDE DIAMETER (MM)	60.00
P7	LENGTH OF BUILDING SUPPLY PIPE (M)	20.00
P8	SURROUNDING TEMP. BUILDING SUPPLY PIPE (C)	20.00
P9	BUILDING SUPPLY PIPE INSIDE DIAMETER (MM)	75.00

P10	LENGTH OF BUILDING RETURN PIPE (M).....	20.00
P11	SURROUNDING TEMP. BUILDING RETURN PIPE (C).....	20.00
P12	BUILDING RETURN PIPE INSIDE DIAMETER (MM).....	75.00
P13	RSI VALUE OF COLLECTOR PIPE INSUL. (M2-C/W).....	1.00
P14	RSI VALUE OF BUILDING PIPE INSUL. (M2-C/W).....	1.00

L. WATER LOAD DATA

L1	HOT WATER SET TEMPERATURE (C).....	49.00
L2	AVERAGE MAINS WATER TEMPERATURE (C).....	10.00
L3	MINIMUM MAINS WATER TEMPERATURE (C).....	5.00
L4	DHW HX EFFECTIVENESS.....	.80
L5	DAYS PER WEEK AT LOAD PROFILE 1	7.00
L6	DAILY HOT WATER LOAD AT LOAD PROFILE 1 (L/DAY)..	1140.00
L7	DAILY HOT WATER LOAD AT LOAD PROFILE 2 (L/DAY)..	.00
L8	HOURLY HOT WATER PROFILE 1 (PERCENT).....	100.00
	.000 .000 .000 .000 .000 .000	
	4.440 11.110 2.220 20.000 2.220 4.440	
	2.220 .000 .000 4.440 11.110 20.000	
	11.110 4.440 2.220 .000 .000 .000	
L9	HOURLY HOT WATER PROFILE 2 (PERCENT).....	100.00
	.000 .000 .000 .000 .000 .000	
	.000 10.000 10.000 10.000 10.000 10.000	
	10.000 10.000 10.000 10.000 10.000 .000	
	.000 .000 .000 .000 .000 .000	

B. BUILDING DATA

B1	BUILDING UA COEFF. (W/C).....	933.00
B2	BUILDING UA COEFF. (ABOVE GRADE) (W/C).....	217.00
B3	POWER FOR HEATING FAN/PUMPS (W).....	1150.00
B4	STORAGE-BUILDING HX EFFECTIVENESS.....	1.00
B5	MIN.CAPACITANCE RATE OF LOAD HX.(W/C).....	7310.00
B6	DIRECT SOLAR GAIN FACTOR (M2).....	29.00
B7	INDOOR DESIGN TEMPERATURE (C).....	22.00
B8	DAILY INTERNAL HEAT GAIN (MJ).....	575.00
B9	HOURLY INTERNAL HEAT GAIN SCHEDULE (%).....	100.00
	.000 .000 .000 .000 .000 2.500	
	4.900 3.700 7.400 6.200 2.500 4.900	
	6.200 4.900 3.700 3.700 2.500 22.200	
	8.600 3.700 3.700 3.700 2.500 2.500	

CITY DATA

LOCATION AND LATITUDE.....AYLMER 43.0

* COLLECTOR AREA : 229.60 M2
* STORAGE VOLUME : ******** LITRES

* ENERGY ANALYSIS SUMMARY *

M	SOLAR INCIDENT (GJ)	SOLAR COLLECT (GJ)	SOLAR DELIVER (GJ)	HT PUMP DELIVER (GJ)	SPACE HT LOAD (GJ)	AUX. SPACE HT (GJ)	WATER LOAD (GJ)	AUX. WATER HT (GJ)	PUMP POWER (GJ)
JAN	56.15	15.95	58.93	.00	55.74	.00	6.30	3.12	1.47
FEB	82.29	38.15	41.05	.00	40.25	1.21	5.86	3.35	1.[illegible]
MAR	94.34	45.86	35.01	.00	33.12	.23	6.48	4.36	2.7[illegible]
APR	121.94	59.93	23.13	.00	20.54	.00	6.09	3.50	2.[illegible]
MAY	97.79	39.25	6.64	.00	2.95	.00	5.96	2.29	1.[illegible]
JUN	88.21	31.68	6.62	.00	2.85	.00	5.40	1.83	1.[illegible]
JUL	120.85	45.18	4.45	.00	.03	.00	5.25	.83	1.[illegible]
AUG	113.14	35.70	4.95	.00	.00	.00	5.06	.12	1.[illegible]
SEP	91.24	25.39	7.24	.00	2.34	.00	4.91	.00	1.[illegible]
OCT	88.75	26.36	14.17	.00	8.90	.00	5.26	.00	1.[illegible]
NOV	47.83	11.67	27.92	.00	22.73	.00	5.41	.23	.[illegible]
DEC	43.75	12.56	42.21	.00	37.58	.00	5.98	1.34	.[illegible]
YR	1046.3	387.7	272.3	.0	227.0	1.4	68.0	21.3	18.7

** TOTAL ENERGY INPUT TO ELECTRIC RESISTANCE REFERENCE SYSTEM OVER SIMULATION PERIOD, GJ : 294.956

** ENERGY SAVING: 85.98 PERCENT

** MAX. HOURLY ENERGY INPUT (MJ): 61.093

** ENERGY GAINED BY STORAGE TANK (GJ): .824

Performance of Aylmer Senior Citizens' Residence - Potential

SOLAR HEATING SYSTEM: -NO HEAT PUMP

C. COLLECTOR DATA

C1	NUMBER OF COLLECTORS	112.00
C2	COLLECTOR SLOPE (DEGREES)	60.00
C3	COLLECTOR ORIENTATION (SOUTH=0,EAST=+, DEG.)	.00
C4	FLUID : 1-WATER, 2-PROP GLYCOL, 3-ETHY GLYCOL	1.00
C5	PERCENTAGE OF FLUID THAT IS GLYCOL (%)	.00
C6	GROSS AREA OF ONE COLLECTOR (M2)	1.73
C7	FR-TAU-ALPHA (TEST)	.73
C8	FR-UL (W/(M2*C)) (TEST)	4.38
C9	COLLECTOR TEST FLOW RATE (L/MIN) (PER COLLECTOR)	3.05
C10	COLL. TEST FLUID 1-WATER,2-PROP GLY,3-ETHY GLY	1.00
C11	PERCENTAGE OF TEST FLUID THAT IS GLYCOL (%)	.00

C12 INCIDENT ANGLE MODIFIER

I	: 1	2	3	4	5
THETA	: 15.000	30.000	45.000	60.000	75.000
AKT	: 1.000	1.000	.930	.800	.700

T. TRANSFER DATA

T1	COLLECTOR-STORAGE HX EFFECTIVENESS	1.00
T2	REQUIRED COLL-STORAGE TEMP. DIFFERENCE (C)	1.70
T3	POWER OF PUMPS 1&2 (W)	2200.00
T4	COLLECTOR LOOP FLOW RATE (L/MIN)	342.00

S. SOLAR STORAGE TANK

S1	VOLUME OF SOLAR STORAGE TANK (LITRES)	********
S2	ORIENTATION: 1 - HORIZONTAL, 2 - VERTICAL	2.00
S3	DIAMETER OF SOLAR STORAGE TANK (M)	6.70
S4	RSI VALUE OF TANK INSULATION (M2-C/W)	8.00
S5	SURROUNDING TEMPERATURE (-100 FOR OUTDOORS)	10.00
S6	LOCATION OF COLLECTOR RETURN CONNECTION	.00
S7	LOCATION OF COLLECTOR SUPPLY CONNECTION	1.00
S8	LOCATION OF MAINS WATER INLET CONNECTION	1.00
S9	LOCATION OF MAINS WATER OUTLET CONNECTION	.00
S10	MAXIMUM STORAGE TANK TEMPERATURE (C)	79.00
S11	MINIMUM ALLOWABLE STORAGE TEMP.(C)	4.00
S12	STARTING TEMPERATURE (C)	32.00

P. COLLECTOR AND BUILDING PIPE DATA

P1	LENGTH OF COLLECTOR SUPPLY PIPE (M)	20.00
P2	SURROUNDING TEMP. COLLECTOR SUPPLY PIPE (C)	20.00
P3	COLLECTOR SUPPLY PIPE INSIDE DIAMETER (MM)	60.00
P4	LENGTH OF COLLECTOR RETURN PIPE (M)	20.00
P5	SURROUNDING TEMP. COLLECTOR RETURN PIPE (C)	20.00
P6	COLLECTOR RETURN PIPE INSIDE DIAMETER (MM)	60.00
P7	LENGTH OF BUILDING SUPPLY PIPE (M)	20.00
P8	SURROUNDING TEMP. BUILDING SUPPLY PIPE (C)	20.00
P9	BUILDING SUPPLY PIPE INSIDE DIAMETER (MM)	75.00

P10	LENGTH OF BUILDING RETURN PIPE (M).....	20.00
P11	SURROUNDING TEMP. BUILDING RETURN PIPE (C).....	20.00
P12	BUILDING RETURN PIPE INSIDE DIAMETER (MM).....	75.00
P13	RSI VALUE OF COLLECTOR PIPE INSUL. (M2-C/W).....	1.00
P14	RSI VALUE OF BUILDING PIPE INSUL. (M2-C/W).....	1.00

L. WATER LOAD DATA

L1	HOT WATER SET TEMPERATURE (C).....	49.00
L2	AVERAGE MAINS WATER TEMPERATURE (C).....	10.00
L3	MINIMUM MAINS WATER TEMPERATURE (C).....	5.00
L4	DHW HX EFFECTIVENESS.....	.80
L5	DAYS PER WEEK AT LOAD PROFILE 1	7.00
L6	DAILY HOT WATER LOAD AT LOAD PROFILE 1 (L/DAY)..	2250.00
L7	DAILY HOT WATER LOAD AT LOAD PROFILE 2 (L/DAY)..	.00
L8	HOURLY HOT WATER PROFILE 1 (PERCENT).....	100.00
	.000 .000 .000 .000 .000 .000	
	4.440 11.110 2.220 20.000 2.220 4.440	
	2.220 .000 .000 4.440 11.110 20.000	
	11.110 4.440 2.220 .000 .000 .000	
L9	HOURLY HOT WATER PROFILE 2 (PERCENT).....	100.00
	.000 .000 .000 .000 .000 .000	
	.000 10.000 10.000 10.000 10.000 10.000	
	10.000 10.000 10.000 10.000 10.000 .000	
	.000 .000 .000 .000 .000 .000	

B. BUILDING DATA

B1	BUILDING UA COEFF. (W/C).....	1113.00
B2	BUILDING UA COEFF. (ABOVE GRADE) (W/C).....	217.00
B3	POWER FOR HEATING FAN/PUMPS (W).....	1150.00
B4	STORAGE-BUILDING HX EFFECTIVENESS.....	1.00
B5	MIN.CAPACITANCE RATE OF LOAD HX.(W/C).....	7310.00
B6	DIRECT SOLAR GAIN FACTOR (M2).....	29.00
B7	INDOOR DESIGN TEMPERATURE (C).....	26.00
B8	DAILY INTERNAL HEAT GAIN (MJ).....	1150.00
B9	HOURLY INTERNAL HEAT GAIN SCHEDULE (%).....	100.00
	.000 .000 .000 .000 .000 2.500	
	4.900 3.700 7.400 6.200 2.500 4.900	
	6.200 4.900 3.700 3.700 2.500 22.200	
	8.600 3.700 3.700 3.700 2.500 2.500	

CITY DATA

LOCATION AND LATITUDE.....AYLMER 43.0

* COLLECTOR AREA : 193.76 M2
* STORAGE VOLUME : ******** LITRES

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* ENERGY ANALYSIS SUMMARY *
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M	SOLAR INCIDENT (GJ)	SOLAR COLLECT (GJ)	SOLAR DELIVER (GJ)	HT PUMP DELIVER (GJ)	SPACE HT LOAD (GJ)	AUX. SPACE HT (GJ)	WATER LOAD (GJ)	AUX. WATER HT (GJ)	PUMP POWER (GJ)
JAN	47.39	15.04	30.14	.00	66.55	40.98	12.44	7.87	3.31
FEB	69.44	29.95	20.24	.00	48.45	32.30	11.56	7.47	3.24
MAR	79.61	34.92	27.10	.00	39.92	17.53	12.79	8.09	3.27
APR	102.91	47.37	27.33	.00	25.47	3.11	12.02	7.04	2.73
MAY	82.52	33.82	10.61	.00	4.28	.00	11.77	5.43	1.90
JUN	74.44	28.57	10.50	.00	4.15	.00	10.66	4.32	1.66
JUL	101.98	40.86	7.52	.00	.08	.00	10.37	2.93	1.97
AUG	95.48	33.24	8.52	.00	.06	.00	10.00	1.54	1.62
SEP	77.00	24.35	12.51	.00	3.74	.00	9.68	.91	1.30
OCT	74.90	25.29	21.46	.00	12.08	.00	10.39	1.01	1.26
NOV	40.36	11.76	36.16	.00	27.75	.00	10.69	2.28	.80
DEC	36.92	12.30	51.75	.00	44.99	.00	11.79	5.03	1.23
YR	883.0	337.5	263.8	.0	277.5	93.9	134.2	53.9	24.3

** TOTAL ENERGY INPUT TO ELECTRIC RESISTANCE REFERENCE SYSTEM OVER SIMULATION PERIOD, GJ : 411.607

** ENERGY SAVING: 58.18 PERCENT

** MAX. HOURLY ENERGY INPUT (MJ): 190.814

** ENERGY GAINED BY STORAGE TANK (GJ): -1.106